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Bedi et al.

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(54) **QUERY LANGUAGE INTEROPERABILITY IN A GRAPH DATABASE**

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(73) Assignee: **Amazon Technologies, Inc.**, Seattle, WA (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

This patent is subject to a terminal disclaimer.

(21) Appl. No.: **18/160,955**

(22) Filed: **Jan. 27, 2023**

(65) **Prior Publication Data**

US 2023/0169117 A1 Jun. 1, 2023

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(63) Continuation of application No. 17/214,334, filed on Mar. 26, 2021, now Pat. No. 11,567,997, which is a (Continued)

(51) **Int. Cl.**
G06F 17/00 (2019.01)
G06F 7/00 (2006.01)
(Continued)

(52) **U.S. Cl.**
CPC ***G06F 16/9024*** (2019.01); ***G06F 16/2452*** (2019.01); ***G06F 16/24542*** (2019.01); ***G06F 16/90335*** (2019.01)

(58) **Field of Classification Search**
CPC G06F 16/9024; G06F 16/2452; G06F 16/90335; G06F 16/24542
(Continued)

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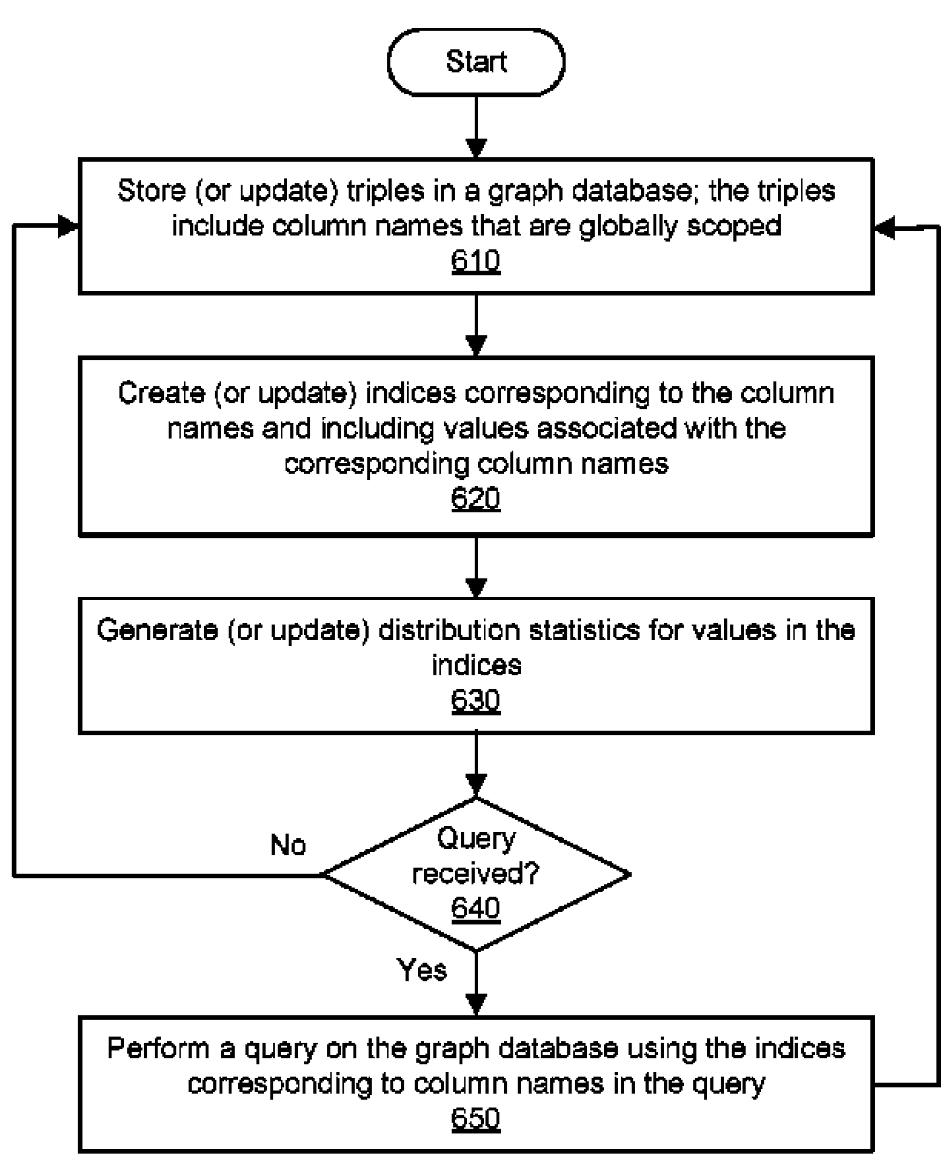
Primary Examiner — Pavan Mamillapalli
(74) *Attorney, Agent, or Firm* — Robert C. Kowert; Kowert, Hood, Munyon, Rankin & Goetzel, P.C.

(57) **ABSTRACT**

Methods, systems, and computer-readable media for query language interoperability in a graph database are disclosed. Data elements are inserted into a graph database using one or more of a plurality of graph database query languages. The graph database query languages comprise a first graph database query language associated with a first data model and a second graph database query language associated with a second data model. The data elements are stored in the graph database using an internal data model that differs from the first and second data models. One or more of the data elements are retrieved from the graph database based at least in part on a query. The query is expressed using a different

(Continued)



graph database query language than the graph database query language used to insert the one or more retrieved data elements.

20 Claims, 18 Drawing Sheets

Related U.S. Application Data

continuation of application No. 15/411,596, filed on Jan. 20, 2017, now Pat. No. 10,963,512.

(51) **Int. Cl.**

G06F 16/2452	(2019.01)
G06F 16/2453	(2019.01)
G06F 16/901	(2019.01)
G06F 16/903	(2019.01)

(58) **Field of Classification Search**
USPC 707/715
See application file for complete search history.

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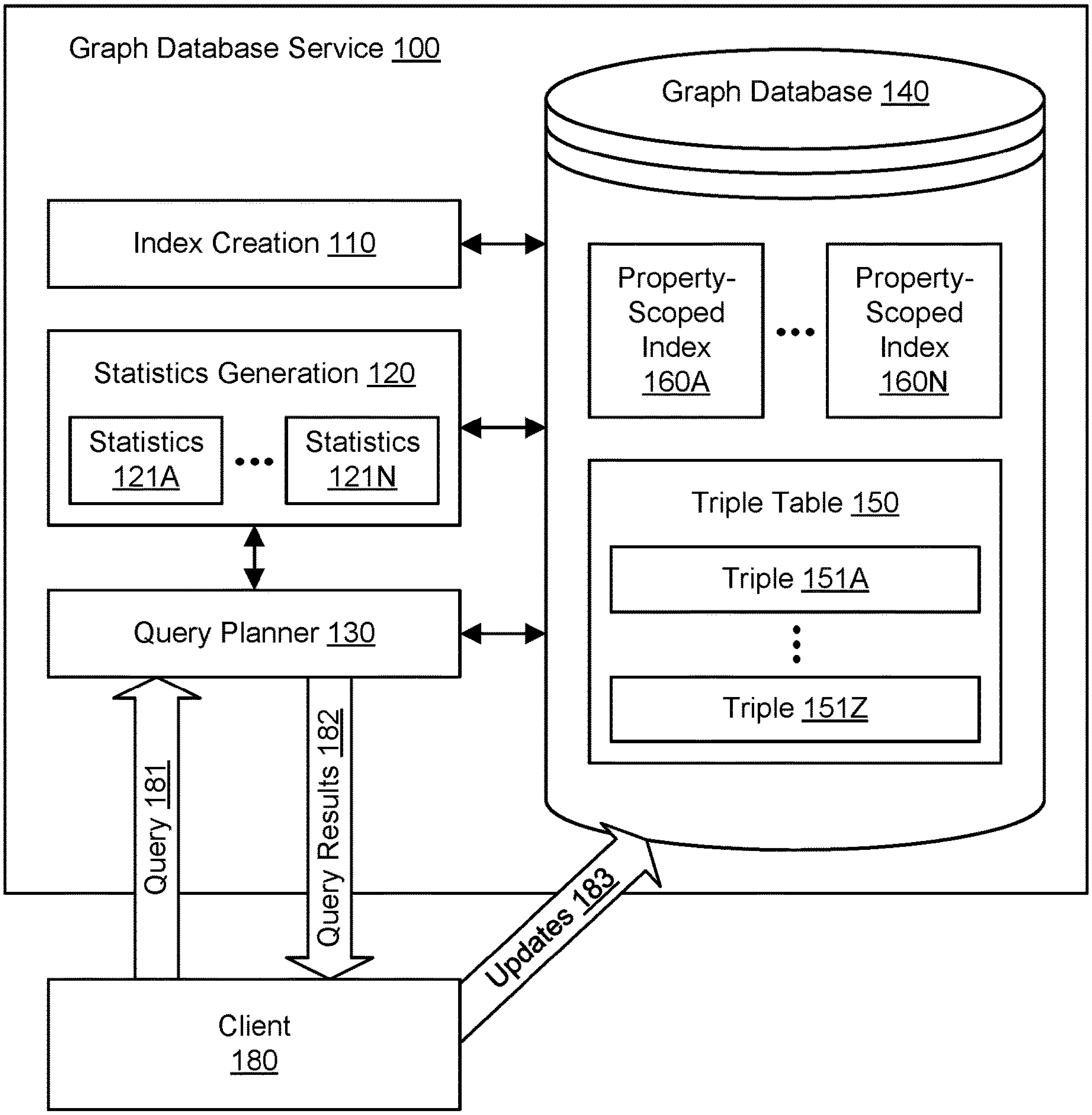


Graph Database Service 100
Graph Database 140
Index Creation 110
Statistics Generation 120
Statistics 121A
Statistics 121N
Property-Scoped Index 160A
Property-Scoped Index 160N
Triple Table 150
Triple 151A
Triple 151Z
Query Planner 130
Query 181
Query Results 182
Updates 183
Client 180

FIG. 1

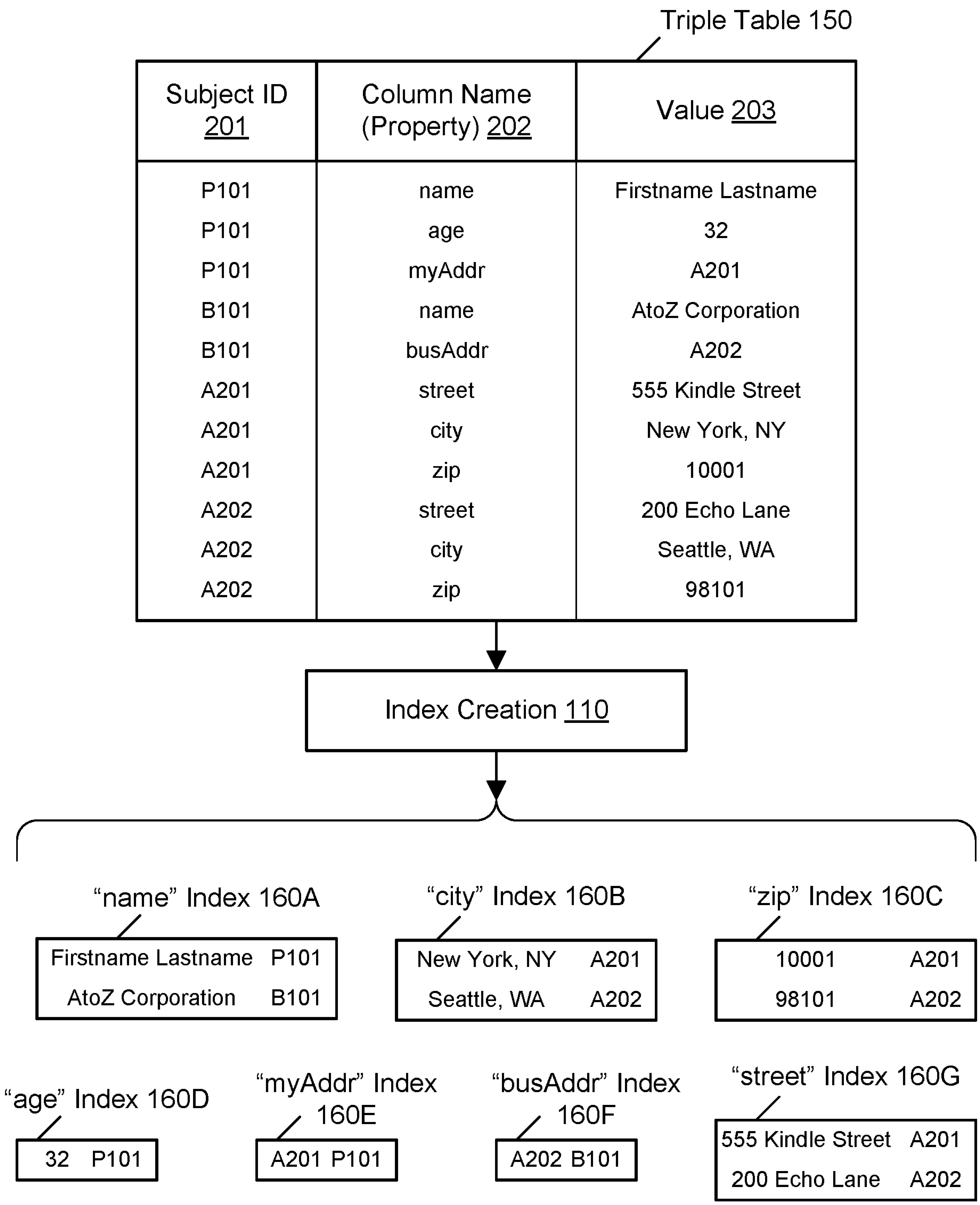

Triple Table 150
Subject ID 201
Column Name (Property) 202
Value 203
P101 name Firstname Lastname
P101 age 32
P101 myAddr A201
B101 name AtoZ Corporation
B101 busAddr A202
A201 street 555 Kindle Street
A201 city New York, NY
A201 zip 10001
A202 street 200 Echo Lane
A202 city Seattle, WA
A202 zip 98101
Index Creation 110
"name" Index 160A
Firstname Lastname P101
AtoZ Corporation B101
"city" Index 160B
New York, NY A201
Seattle, WA A202
"zip" Index 160C
10001 A201
98101 A202
"age" Index 160D
32 P101
"myAddr" Index 160E
A201 P101
"busAddr" Index 160F
A202 B101
"street" Index 160G
555 Kindle Street A201
200 Echo Lane A202

FIG. 2A

Triple Table 150

Subject ID 201	Column Name (Property) 202	Value 203	Graph ID 204
P101	name	Firstname Lastname	G001
P101	age	32	G001
P101	myAddr	A201	G001
B101	name	AtoZ Corporation	G001
B101	busAddr	A202	G001
A201	street	555 Kindle Street	G001
A201	city	New York, NY	G001
A201	zip	10001	G001
A202	street	200 Echo Lane	G002
A202	city	Seattle, WA	G002
A202	zip	98101	G002

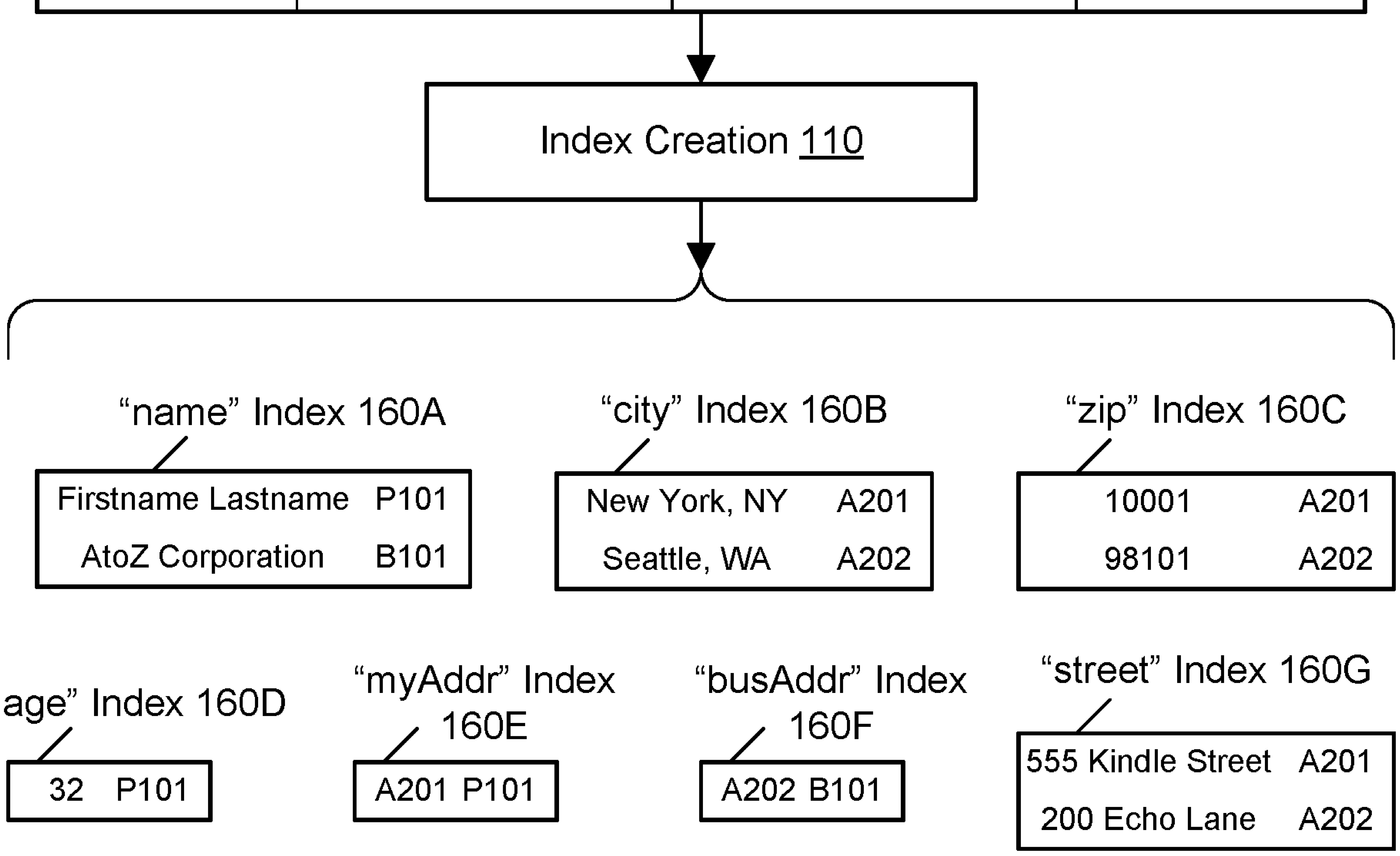


FIG. 2B

Triple Table 150

Subject ID 201	Column Name (Property) 202	Value 203	Annotation 205A	•••	Annotation 205G
P101	name	Firstname Lastname	text1		value1
P101	age	32			value1
P101	myAddr	A201			value1
B101	name	AtoZ Corporation	text2		value2
B101	busAddr	A202			value2
A201	street	555 Kindle Street			value3
A201	city	New York, NY			value3
A201	zip	10001			value3
A202	street	200 Echo Lane			
A202	city	Seattle, WA			
A202	zip	98101			

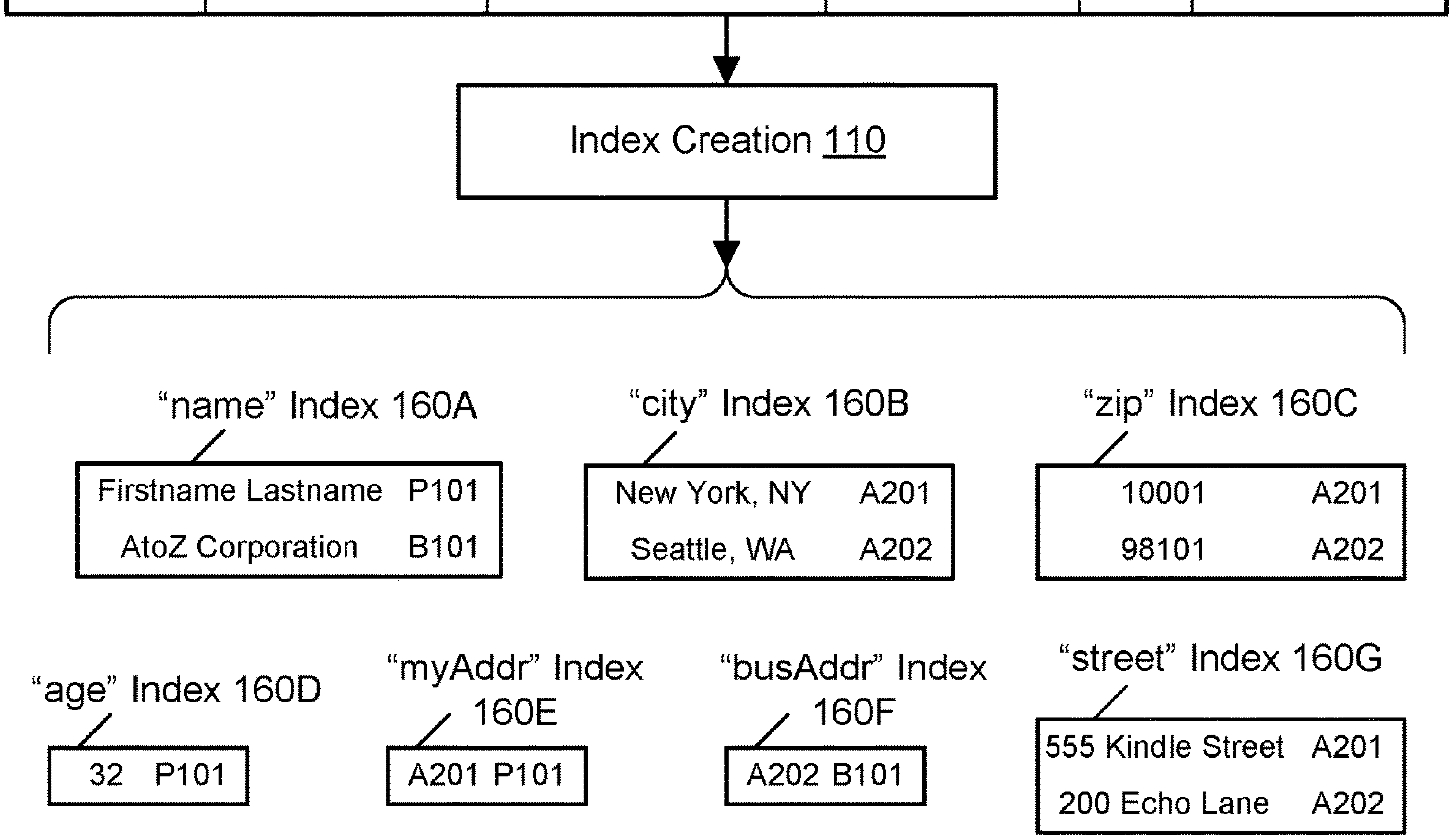


FIG. 2C

Triple Table 150

Subject ID 201	Column Name (Property) 202	Value 203
P101	name	Firstname Lastname
P101	age	32
P101	myAddr	A201
B101	name	AtoZ Corporation
B101	busAddr	A202
A201	street	555 Kindle Street
A201	city	New York, NY
A201	zip	10001
A202	street	200 Echo Lane
A202	city	Seattle, WA
A202	zip	98101

Relational View 210

Person 220

ID	name	age	myAddr
P101	Firstname Lastname	32	A201

Business 230

ID	name	busAddr
B101	AtoZ Corporation	A202

Address 240

ID	street	city	zip
A201	555 Kindle Street	New York, NY	10001
A202	200 Echo Lane	Seattle, WA	98101

FIG. 3

Triple Table 150

Subject ID 201	Column Name (Property) 202	Value 203
P101	name	Firstname Lastname
P101	age	32
P101	myAddr	A201
B101	name	AtoZ Corporation
B101	busAddr	A202
A201	street	555 Kindle Street
A201	city	New York, NY
A201	zip	10001
A202	street	200 Echo Lane
A202	city	Seattle, WA
A202	zip	98101

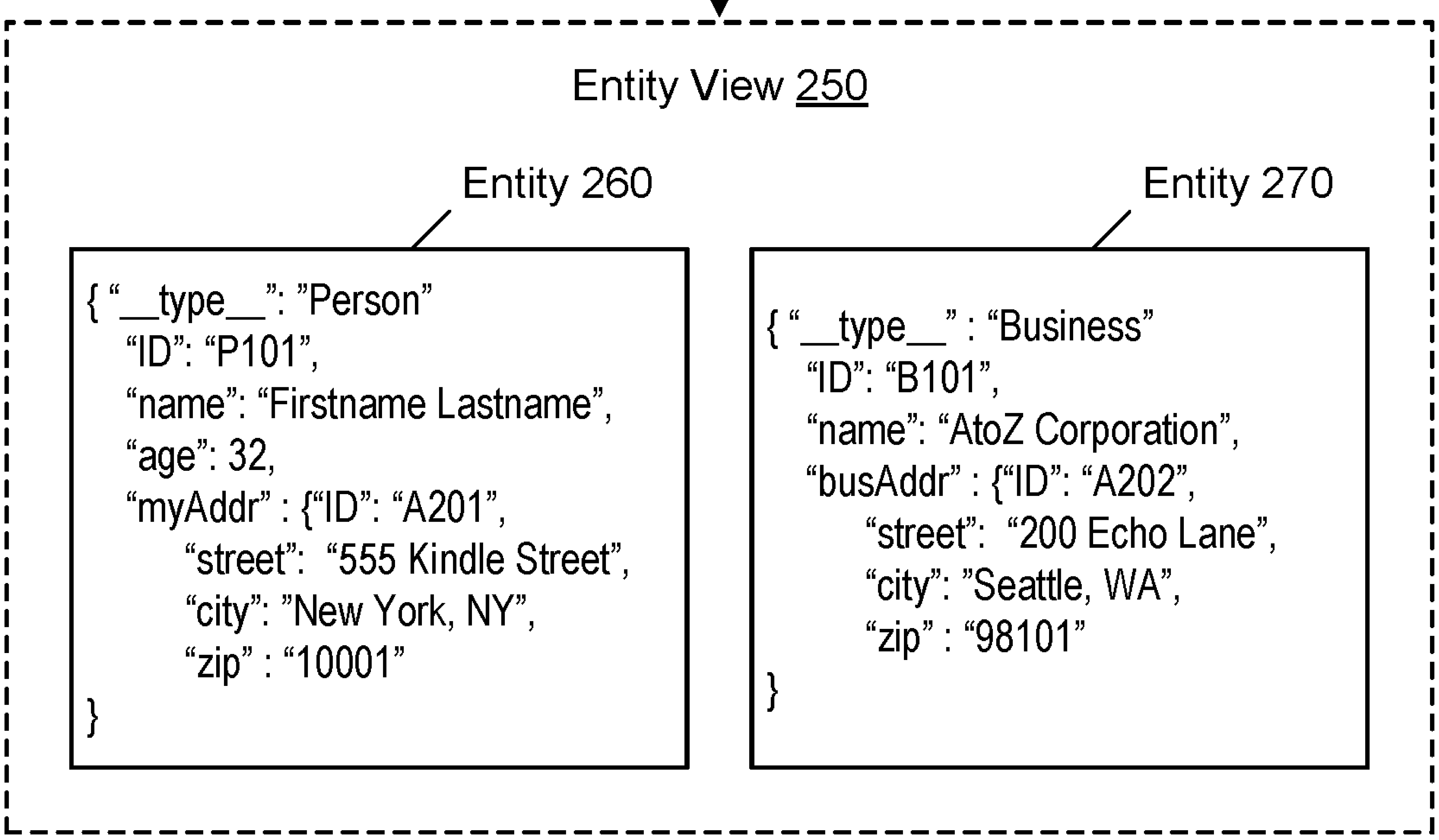
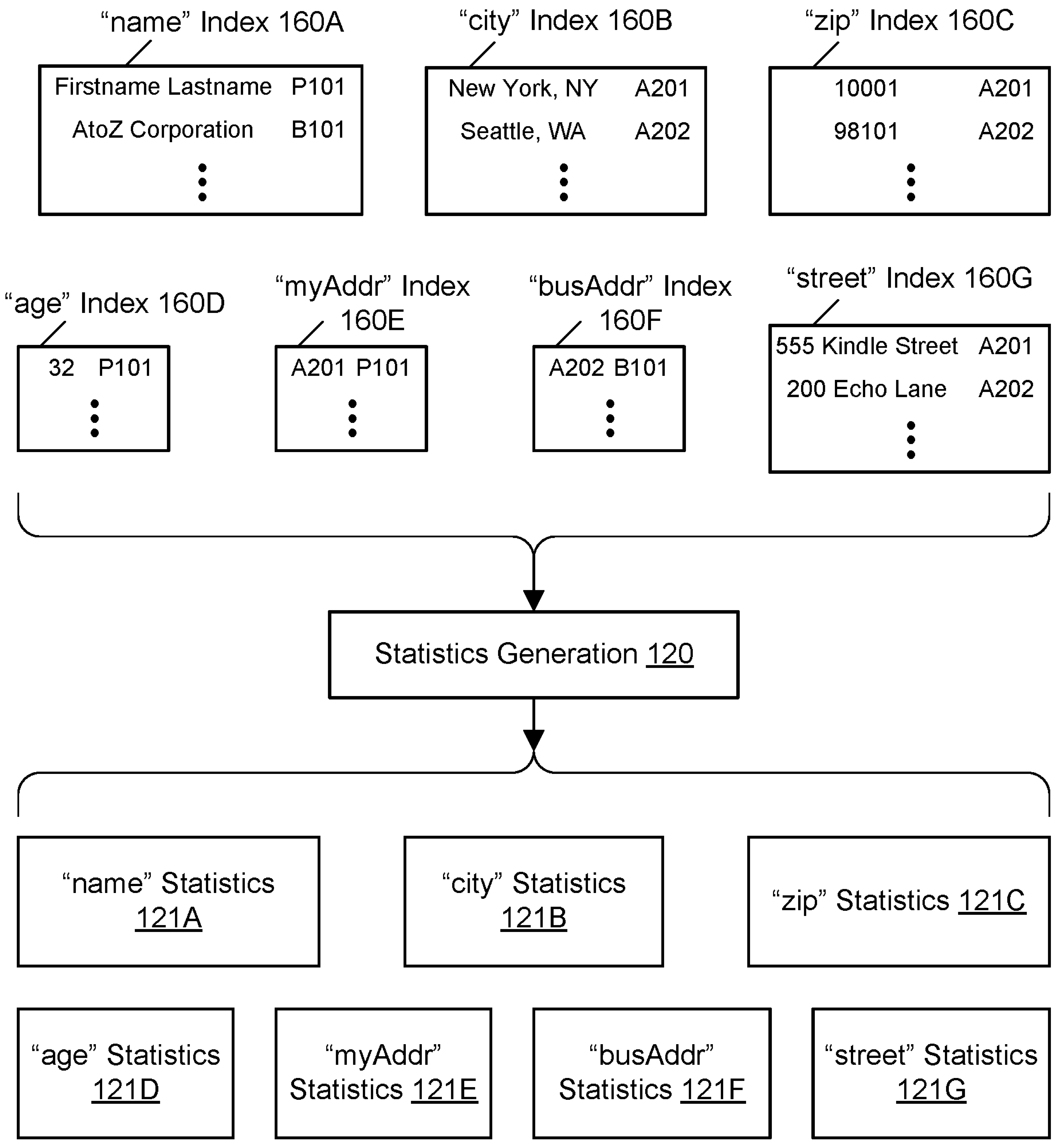


FIG. 4



"name" Index 160A
Firstname Lastname P101
AtoZ Corporation B101
"city" Index 160B
New York, NY A201
Seattle, WA A202
"zip" Index 160C
10001 A201
98101 A202
"age" Index 160D
32 P101
"myAddr" Index 160E
A201 P101
"busAddr" Index 160F
A202 B101
"street" Index 160G
555 Kindle Street A201
200 Echo Lane A202
Statistics Generation 120
"name" Statistics 121A
"city" Statistics 121B
"zip" Statistics 121C
"age" Statistics 121D
"myAddr" Statistics 121E
"busAddr" Statistics 121F
"street" Statistics 121G

FIG. 5

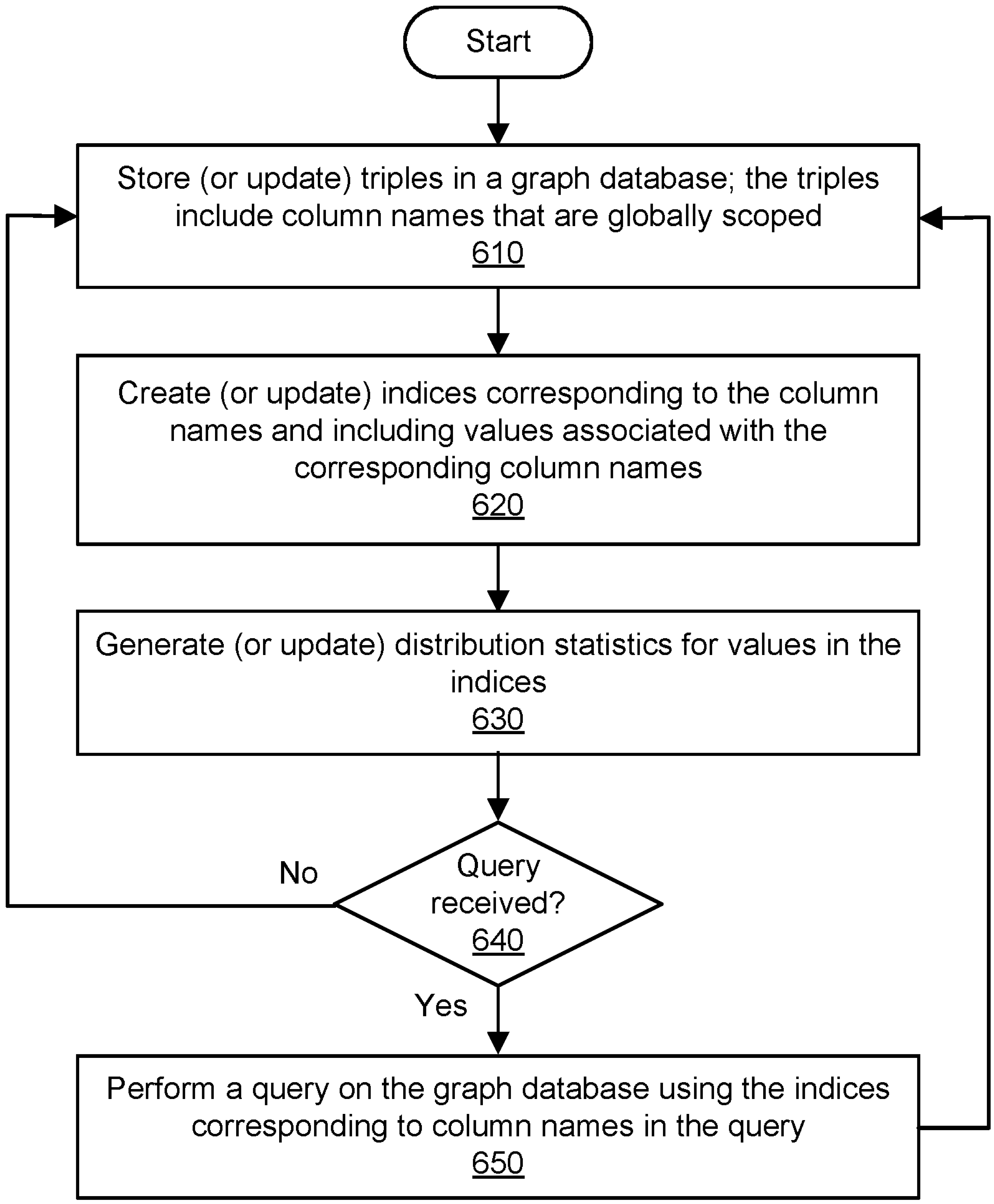

Start
Store (or update) triples in a graph database; the triples include column names that are globally scoped
610
Create (or update) indices corresponding to the column names and including values associated with the corresponding column names
620
Generate (or update) distribution statistics for values in the indices
630
Query received?
640
No
Yes
Perform a query on the graph database using the indices corresponding to column names in the query
650

FIG. 6

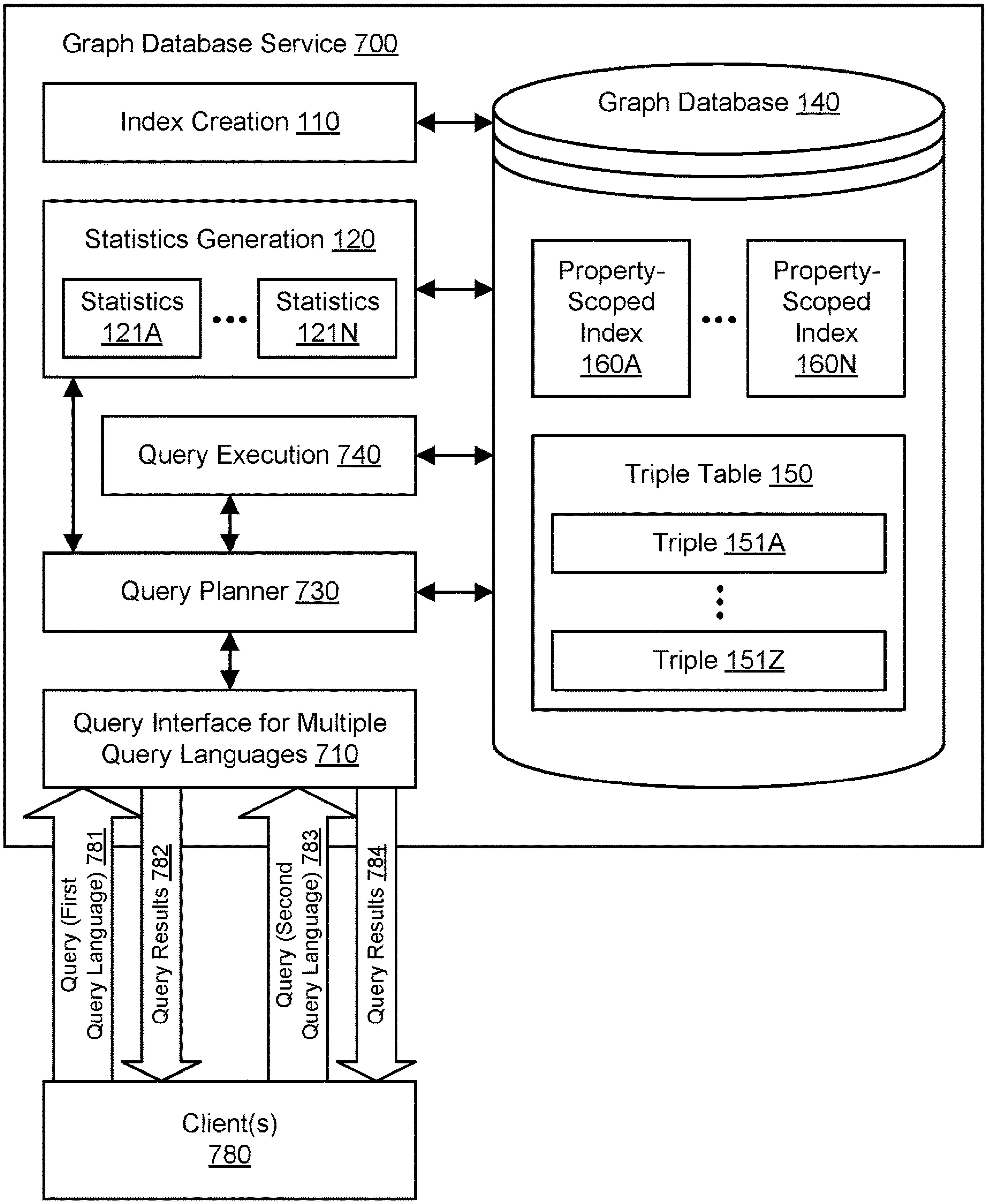

Graph Database Service 700
Index Creation 110
Statistics Generation 120
Statistics 121A
Statistics 121N
Query Execution 740
Query Planner 730
Query Interface for Multiple Query Languages 710
Graph Database 140
Property-Scoped Index 160A
Property-Scoped Index 160N
Triple Table 150
Triple 151A
Triple 151Z
Query (First Query Language) 781
Query Results 782
Query (Second Query Language) 783
Query Results 784
Client(s) 780

FIG. 7

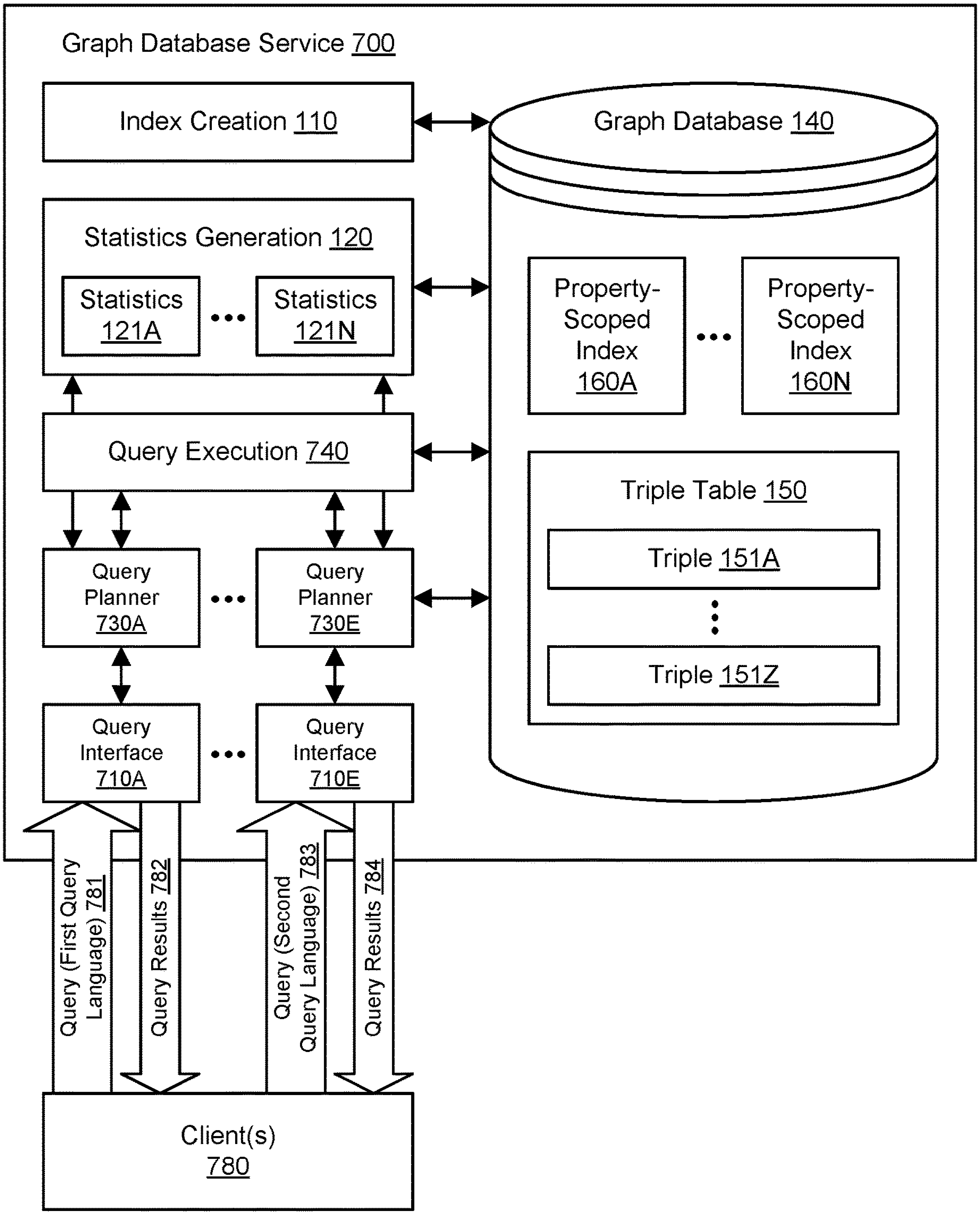
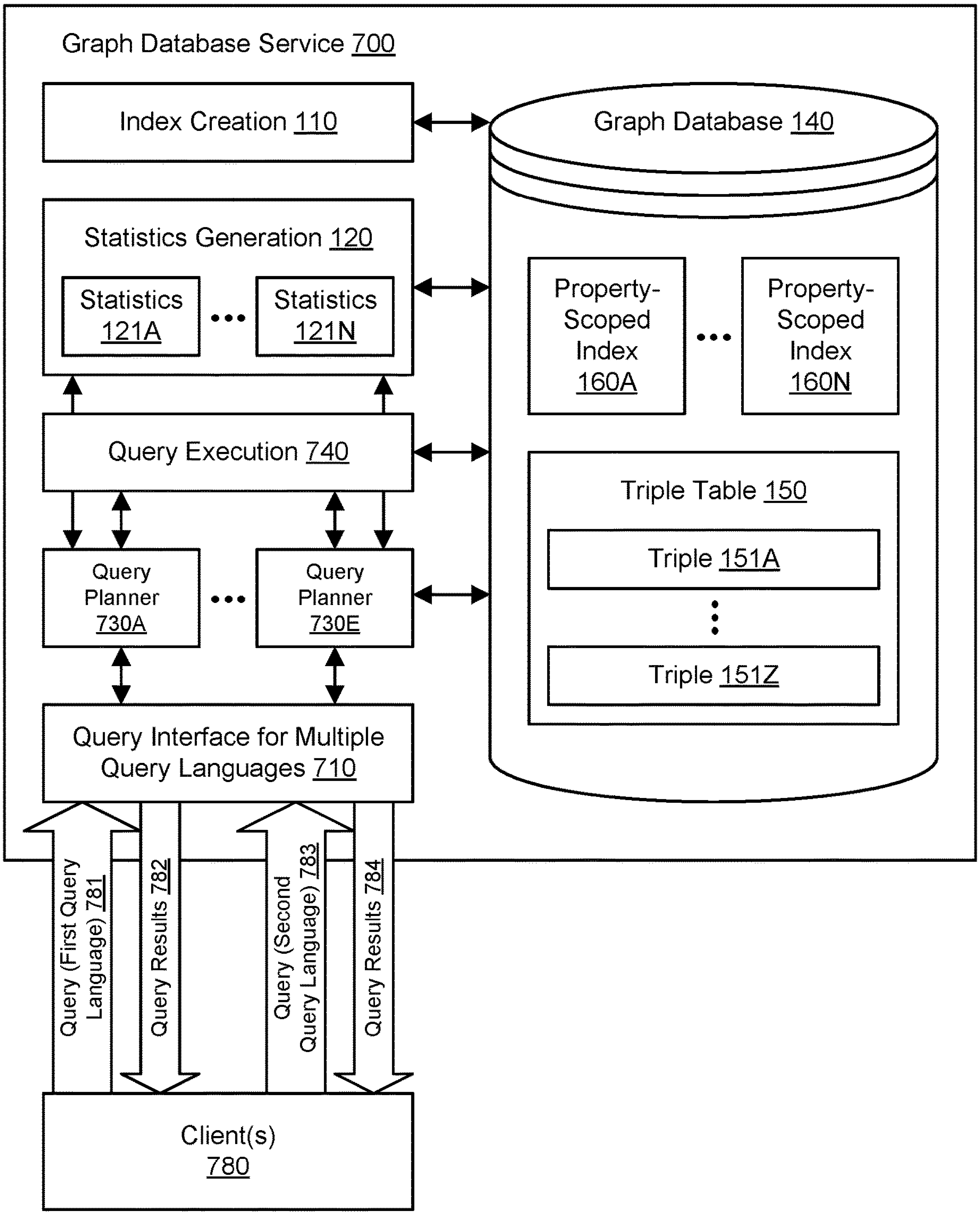
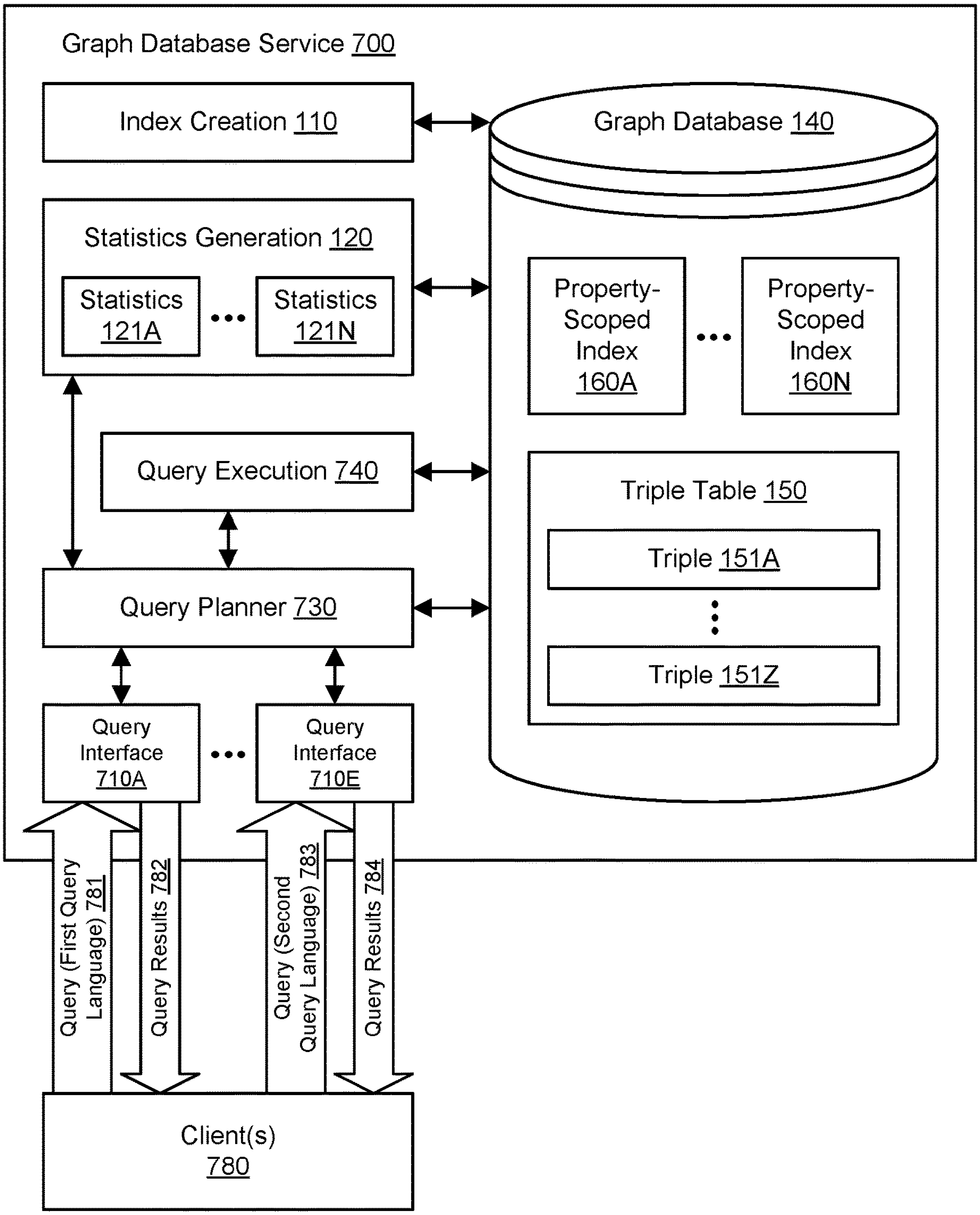

Graph Database Service 700
Index Creation 110
Statistics Generation 120
Statistics 121A
Statistics 121N
Query Execution 740
Query Planner 730A
Query Planner 730E
Query Interface 710A
Query Interface 710E
Graph Database 140
Property-Scoped Index 160A
Property-Scoped Index 160N
Triple Table 150
Triple 151A
Triple 151Z
Query (First Query Language) 781
Query Results 782
Query (Second Query Language) 783
Query Results 784
Client(s) 780

FIG. 8A



Graph Database Service 700
Index Creation 110
Graph Database 140
Statistics Generation 120
Statistics 121A
Statistics 121N
Property-Scoped Index 160A
Property-Scoped Index 160N
Query Execution 740
Triple Table 150
Triple 151A
Query Planner 730A
Query Planner 730E
Triple 151Z
Query Interface for Multiple Query Languages 710
Query (First Query Language) 781
Query Results 782
Query (Second Query Language) 783
Query Results 784
Client(s) 780

FIG. 8B



Graph Database Service 700
Index Creation 110
Graph Database 140
Statistics Generation 120
Statistics 121A
Statistics 121N
Property-Scoped Index 160A
Property-Scoped Index 160N
Query Execution 740
Triple Table 150
Triple 151A
Triple 151Z
Query Planner 730
Query Interface 710A
Query Interface 710E
Query (First Query Language) 781
Query Results 782
Query (Second Query Language) 783
Query Results 784
Client(s) 780

FIG. 8C

Triple Table 150

Subject ID 201	Column Name (Property) 202	Value 203
P101	name	Firstname Lastname
P101	age	32
P101	myAddr	A201
B101	name	AtoZ Corporation
B101	busAddr	A202
A201	street	555 Kindle Street
A201	city	New York, NY
A201	zip	10001
A202	street	200 Echo Lane
A202	city	Seattle, WA
A202	zip	98101
P105	type	Customer
P105	name	Name Surname
P105	age	27

Data Model Mapping 720

```
INSERT DATA
{
    <P105> type    <Customer>
    <P105> name    "Name Surname"
    <P105> age     27
}
```

RDF-Based Insertion Query 900

FIG. 9

Triple Table 150

Subject ID 201	Column Name (Property) 202	Value 203
P101	name	Firstname Lastname
P101	age	32
P101	myAddr	A201
B101	name	AtoZ Corporation
B101	busAddr	A202
A201	street	555 Kindle Street
A201	city	New York, NY
A201	zip	10001
A202	street	200 Echo Lane
A202	city	Seattle, WA
A202	zip	98101
P105	type	Customer
P105	name	Name Surname
P105	age	27

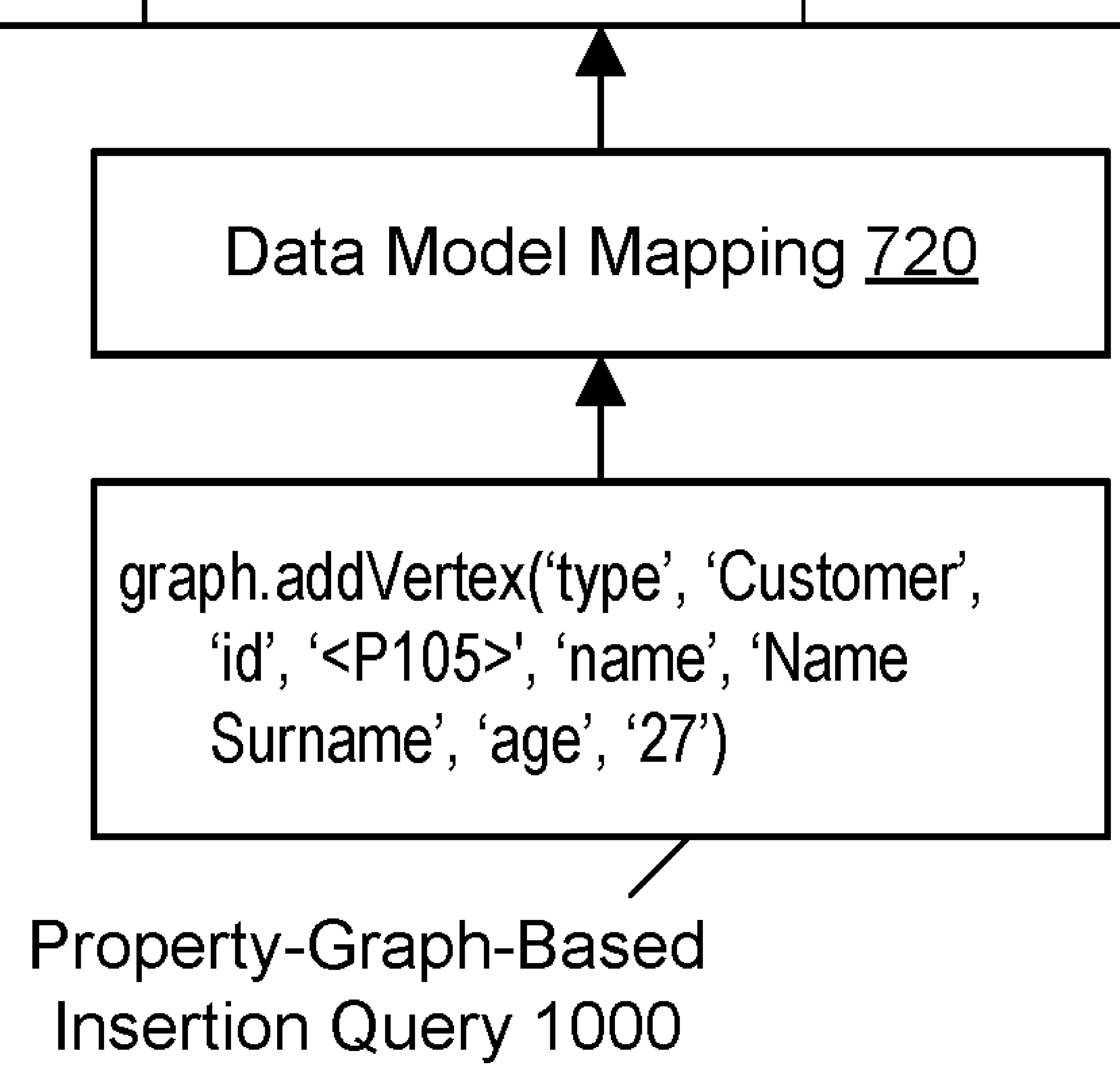


FIG. 10

Triple Table 150

Subject ID 201	Column Name (Property) 202	Value 203
P101	name	Firstname Lastname
P101	age	32
P101	myAddr	A201
B101	name	AtoZ Corporation
B101	busAddr	A202
A201	street	555 Kindle Street
A201	city	New York, NY
A201	zip	10001
A202	street	200 Echo Lane
A202	city	Seattle, WA
A202	zip	98101
P105	type	Customer
P105	name	Name Surname
P105	age	27

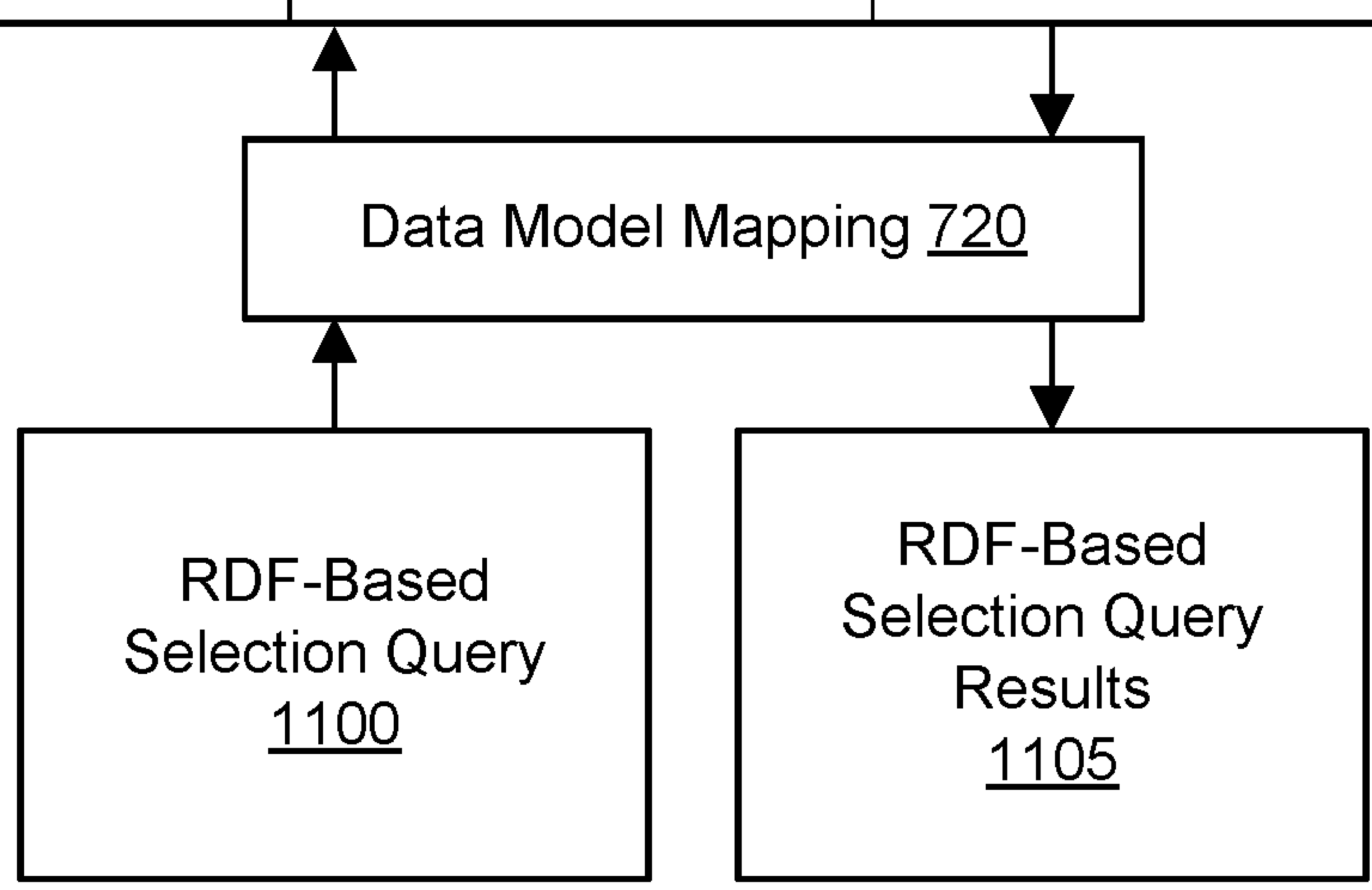


FIG. 11

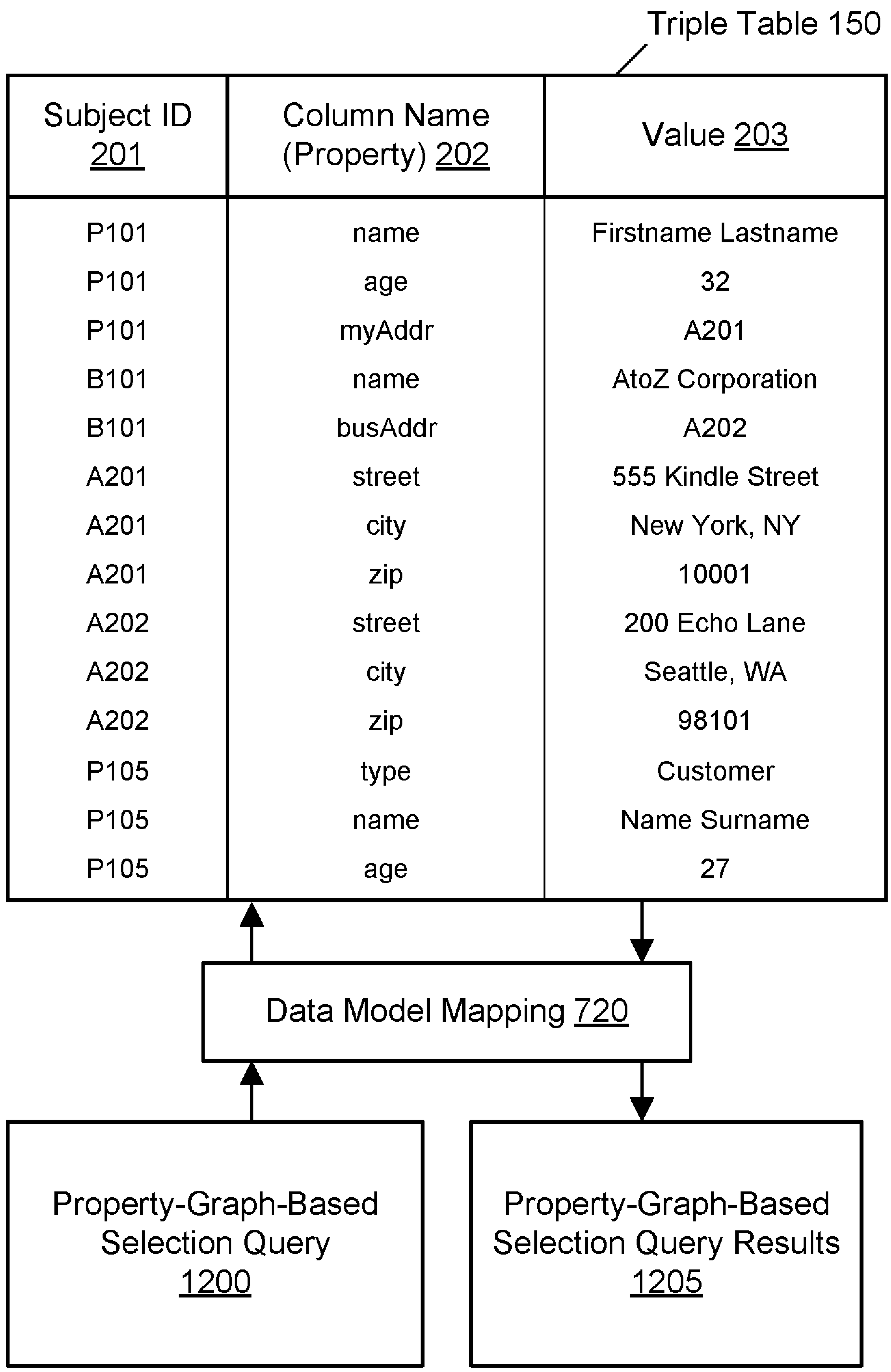

Triple Table 150
Subject ID 201
Column Name (Property) 202
Value 203
P101 name Firstname Lastname
P101 age 32
P101 myAddr A201
B101 name AtoZ Corporation
B101 busAddr A202
A201 street 555 Kindle Street
A201 city New York, NY
A201 zip 10001
A202 street 200 Echo Lane
A202 city Seattle, WA
A202 zip 98101
P105 type Customer
P105 name Name Surname
P105 age 27
Data Model Mapping 720
Property-Graph-Based Selection Query 1200
Property-Graph-Based Selection Query Results 1205

FIG. 12

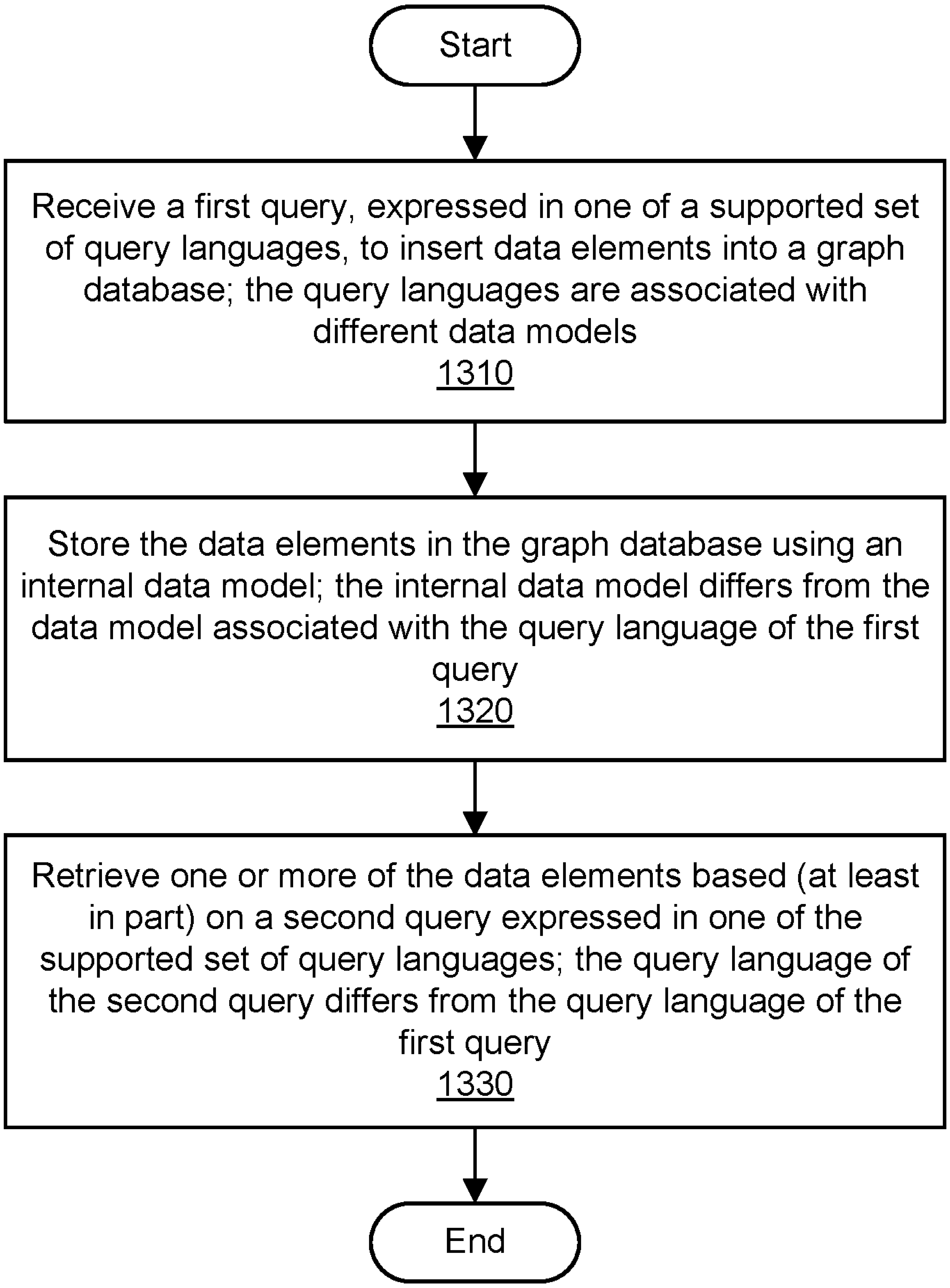

Start
Receive a first query, expressed in one of a supported set of query languages, to insert data elements into a graph database; the query languages are associated with different data models
1310
Store the data elements in the graph database using an internal data model; the internal data model differs from the data model associated with the query language of the first query
1320
Retrieve one or more of the data elements based (at least in part) on a second query expressed in one of the supported set of query languages; the query language of the second query differs from the query language of the first query
1330
End

FIG. 13

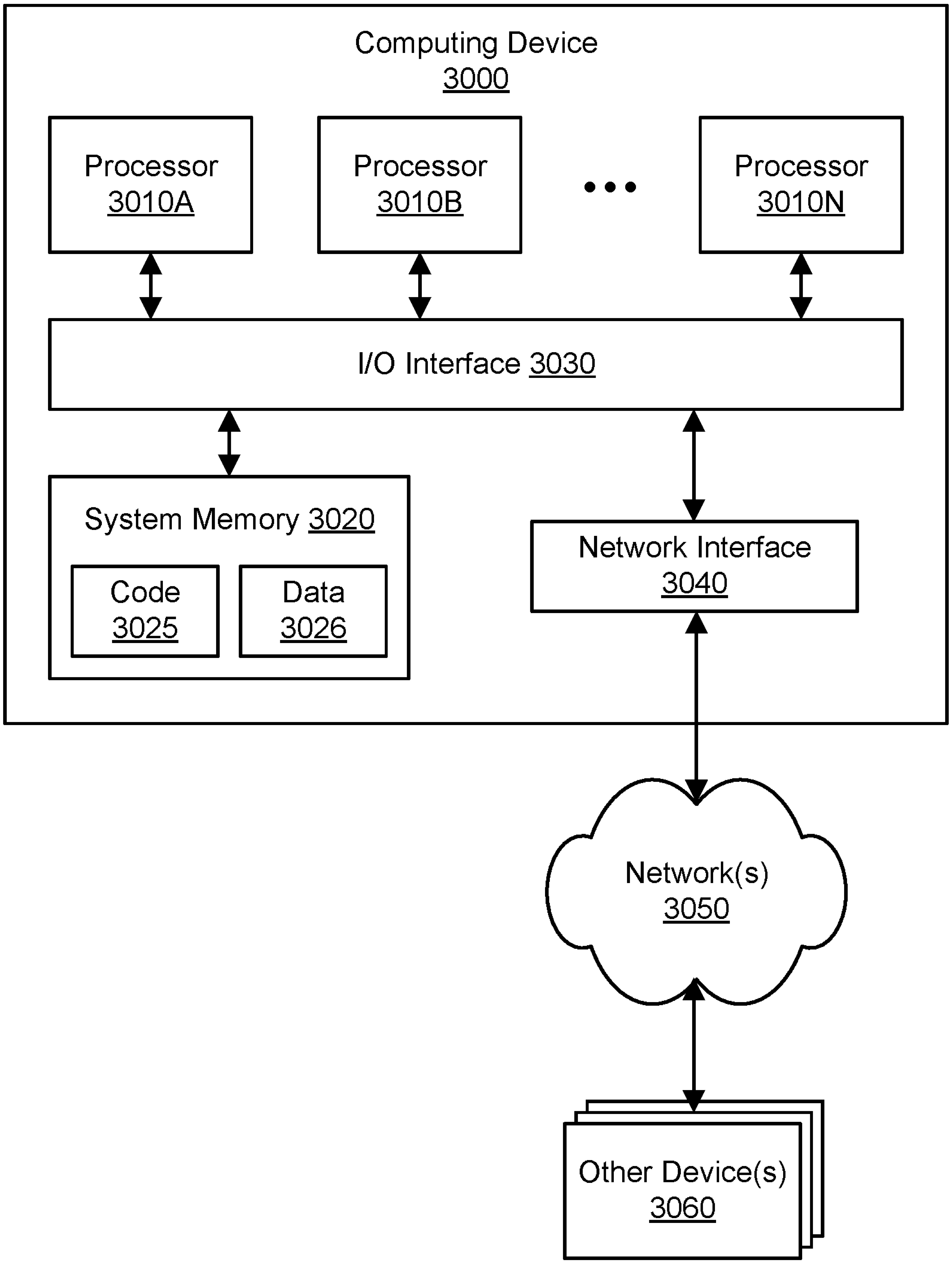

Computing Device
3000
Processor
3010A
Processor
3010B
Processor
3010N
I/O Interface 3030
System Memory 3020
Code
3025
Data
3026
Network Interface
3040
Network(s)
3050
Other Device(s)
3060

FIG. 14

QUERY LANGUAGE INTEROPERABILITY IN A GRAPH DATABASE

This application is a continuation of U.S. patent application Ser. No. 17/214,334, filed Mar. 26, 2021, which is a continuation of U.S. patent application Ser. No. 15/411,596, filed Jan. 20, 2017, now U.S. Pat. No. 10,963,512, which are hereby incorporated by reference herein their entirety.

BACKGROUND

As an increasing amount of data is generated, the need for storage and analysis of such data is similarly growing. In varied domains such as social media, mobile and messaging apps, web portals, and the Internet of Things (IoT), data may be both rich and highly connected. New relationships between data elements may be created at a high rate, and effective analysis of such data may often include analysis of the relationships. For example, modeling a social network may include modeling relationships between people. The relationships may change over time, and information relating to the people themselves may be added or modified over time as well. Applications that seek to analyze such information may require prompt answers to complex questions regarding networks of relationships, such as purchases or preferences relating to friends of a particular person.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** illustrates an example system environment for global column indexing in a graph database, according to one embodiment.

FIG. **2**A through FIG. **2**C illustrate examples of a graph database usable with the example system environment, including the creation of per-column indices for globally scoped column names, according to one embodiment.

FIG. **3** illustrates an example of a graph database usable with the example system environment, including a relational view of data elements in the graph database, according to one embodiment.

FIG. **4** illustrates an example of a graph database usable with the example system environment, including an entity view of data elements in the graph database, according to one embodiment.

FIG. **5** illustrates the generation of statistics associated with per-column indices for globally scoped column names, according to one embodiment.

FIG. **6** is a flowchart illustrating a method for global column indexing in a graph database, according to one embodiment.

FIG. **7** illustrates an example system environment for query language interoperability in a graph database, according to one embodiment.

FIG. **8**A, FIG. **8**B, and FIG. **8**C illustrate further aspects of the example system environment for query language interoperability in a graph database, including separate components for multiple query languages in a query pipeline, according to one embodiment.

FIG. **9** illustrates an example of a graph database that supports query language interoperability, including insertion of data elements expressed according to a resource description framework (RDF) data model, according to one embodiment.

FIG. **10** illustrates an example of a graph database that supports query language interoperability, including insertion of data elements expressed according to a property graph data model, according to one embodiment.

FIG. **11** illustrates an example of a graph database that supports query language interoperability, including retrieval of data elements expressed according to an RDF data model, according to one embodiment.

FIG. **12** illustrates an example of a graph database that supports query language interoperability, including retrieval of data elements expressed according to a property graph data model, according to one embodiment.

FIG. **13** is a flowchart illustrating a method for implementing query language interoperability in a graph database, according to one embodiment.

FIG. **14** illustrates an example computing device, according to one embodiment.

While embodiments are described herein by way of example for several embodiments and illustrative drawings, those skilled in the art will recognize that embodiments are not limited to the embodiments or drawings described. It should be understood, that the drawings and detailed description thereto are not intended to limit embodiments to the particular form disclosed, but on the contrary, the intention is to cover all modifications, equivalents and alternatives falling within the spirit and scope as defined by the appended claims. The headings used herein are for organizational purposes only and are not meant to be used to limit the scope of the description or the claims. As used throughout this application, the word "may" is used in a permissive sense (i.e., meaning "having the potential to"), rather than the mandatory sense (i.e., meaning "must"). Similarly, the words "include," "including," and "includes" mean "including, but not limited to."

DETAILED DESCRIPTION OF EMBODIMENTS

Various embodiments of methods, systems, and computer-readable media for query language interoperability in a graph database are described. In one embodiment, a graph database stores data elements using an internal data model. In one embodiment, for example, the internal data model may represent data elements using triples, and a triple may include a subject identifier, a column name, and a value. In one embodiment, the triples in the graph database may be used to represent nodes and edges (relationships) in a graph of connected items. In one embodiment, the graph database may provide access to data elements using a plurality of query languages, and the data models associated with the query languages may differ from the internal data model. In one embodiment, the graph database may support queries expressed in a graph database query language typically used for semantic queries and whose data model represents the data elements as resource description framework (RDF) triples comprising subjects, predicates, and objects. In one embodiment, the graph database may support queries expressed in a graph database query language typically used for graph traversal queries and whose data model represents the data elements as property graphs. In one embodiment, the graph database may provide interoperability for the multiple query languages and the corresponding multiple data models. For example, in one embodiment, a query expressed in a first query language may insert data elements into the graph database, where the inserted data elements are mapped from a first data model to the internal data model; the same data elements may be retrieved using a query expressed in a second query language, where the retrieved data elements are mapped from the internal data model to a second data model. In one embodiment, a graph database may provide users with a variety of features associated with different query languages while maintaining the underlying data using a unified, common storage scheme.

In one embodiment, columns in the internal data model are strongly typed such that values in a particular column may share the same data type. In one embodiment, column names are globally scoped in the internal data model of the graph database, such that the same column name may not be represented more than once in the graph database and may not be limited to a particular sub-table of the graph database. In one embodiment, the graph database service uses a partitioned indexing scheme to enable querying of the graph database. In one embodiment, indices are created and maintained for global columns in the primary table in the graph database. In one embodiment, a per-column index may be a table or other columnar data structure that includes multiple rows, and each row may include the values associated with the column corresponding to the index. In one embodiment, the indices may effectively be partitioned by column name. In one embodiment, the generation and maintenance of indices is performed by the graph database service automatically, e.g., without being directly prompted by user input directing the indexing tasks. In one embodiment, the per-column indices are used to perform queries of the graph database. In one embodiment, to perform a query, a query planner may refer to the indices corresponding to columns associated with the query. In one embodiment, statistics are generated and maintained for the indices in order to optimize queries. In one embodiment, the statistics for an index may represent distributions of values within the corresponding column. In one embodiment, to optimize a query, the order of indices to be used may be determined based (at least in part) on the statistics for the per-column indices. In one embodiment, statistics may be maintained automatically and in real time or near-real time to enable optimized query processing using up-to-date information.

FIG. **1** illustrates an example system environment for global column indexing in a graph database, according to one embodiment. In one embodiment, a graph database service **100** stores elements of data in a graph database **140**. In one embodiment, the graph database may also be referred to as a graph data store or a triple store. In one embodiment, a graph represented by the graph database service **100** is a data structure that is suitable for representing relationships, connections, and dependencies within data. In one embodiment, typical examples of domains in which graphs can model data may include social networks or communication networks, biological networks, time series applications, and metadata management. In one embodiment, a graph may include nodes (vertices) and edges (relationships) as well as properties associated with those vertices and edges. In one embodiment, a node may represent a concept or an object. In one embodiment, an edge may represent a relationship between vertices. In one embodiment, a vertex may have various properties such as a name. In one embodiment, an edge may have various properties such as a type of relationship. In one embodiment, for example, in a graph within a social network, User1, User2, and User3 may be entities, and a "friendOf" relationship between them may define the "edges" of this small graph. In one embodiment, the User1, User2, and User3 entities may have properties like "name" and "age," and the relationship properties may include "start date," "source," and so on. In one embodiment, large volumes of such connected data may be generated from modern applications, mobile and messaging apps, and IoT devices. In one embodiment, such data tends to be dynamic, such that the relationships, entities, and their properties may be constantly changing.

Schema-based relational data stores may not be able to change rapidly enough; schema-less stores like key-value stores may be unable to work with sophisticated query languages. Traditional key-value data stores and relational data stores may often be unwieldy for managing data that is rich and highly connected. In one embodiment, for example, key-value stores may support accessing discrete objects that do not necessarily represent rich data or relationships. As another example, relational data stores may be too inflexible to adequately represent the fluid relationships in highly connected data. When relational databases are used to store such data, developers may be required to store the data in tables with rigid structures and write complex SQL queries using multiple joins. Such complex queries may prove difficult to maintain and may not scale adequately when run on large datasets. As the data scale increases, some graphs may become billion-edge structures that challenge prior hardware and software solutions. In one embodiment, the graph database service **100** may query such data efficiently using per-column (property-scoped) indices **160**A-**160**N. Although indices **160**A-**160**N are illustrated for purposes of example, any suitable number and configuration of indices may be used in the graph database in various embodiments.

In one embodiment, the elements of data in the graph database may represent triples or rows in a columnar format. In one embodiment, triples such as triples **151**A through **151**Z may be stored in a triple table **150**; the triple table may represent a primary table in the graph database. Although triples **151**A-**151**Z are illustrated for purposes of example, any suitable number and configuration of triples may be used in the graph database in various embodiments. In one embodiment, for example, a triple may include an identifier, a column name, and a value. In one embodiment, triples may include different elements than (e.g., in addition to or instead of) an identifier, column name, and value. In one embodiment, the identifier may also be referred to as a subject identifier. In one embodiment, the identifier may indicate the particular row (e.g., in a relational view of the data) or record that holds the combination of the column name and the value in the triple. In one embodiment, the same subject identifier may be reused for multiple triples, e.g., if the corresponding row or record includes values in multiple categories. In one embodiment, the column name may indicate a distinct and separate category of data, and the value may represent one of the allowable values within the category. In one embodiment, the triples in a graph database may be used to represent nodes and edges (relationships) in a graph of connected items. In one embodiment, the graph database may store one graph or multiple graphs. In one embodiment, the triples are also stored with graph identifiers that indicate particular graphs or sub-graphs to which the triples belong.

In one embodiment, columns are strongly typed such that values in a particular column may share the same data type, and an enforcement mechanism may ensure that values in the particular column are limited to being expressed in the data type associated with the column. In one embodiment, data types may differ from column to column. In one embodiment, all the rows and columns in the graph database may effectively belong to the same primary table, e.g., the triple table. In one embodiment, column names are globally scoped in the graph database, such that the same column name may not be represented more than once in the graph database and may not be limited to a particular sub-table of the graph database. In one embodiment, by way of contrast, column names in a conventional relational database are typically locally scoped to one of many tables.

In one embodiment, the graph database service **100** uses a partitioned indexing scheme to enable querying of the graph database. In one embodiment, an index creation component **110** may create and maintain indices for every global column in the primary table in the graph database. In one embodiment, the index creation component **110** may create and maintain indices for many but not necessarily all global columns in the primary table in the graph database, e.g., for columns that are intended to be queryable or searchable. In one embodiment, a per-column index may be a table or other columnar data structure that includes multiple rows, and each row may include the values associated with the column corresponding to the index. In one embodiment, a per-column index may also be referred to as a property-scoped index. In one embodiment, each row in a per-column index also includes a pointer to the corresponding row in the primary table in the graph database. In one embodiment, the indices **160**A-**160**N may be stored as separate data structures from each other and from the triple table **150**, e.g., in storage managed by or otherwise accessible to the graph database service **100**. In one embodiment, the indices may effectively be partitioned by column name. In one embodiment, by way of contrast, such per-column indexing in a conventional relational database would often be prohibitively expensive due to the vastly greater number of locally scoped columns that may be managed in a relational database management system. In one embodiment, the generation and maintenance of indices is performed by the graph database service **100** automatically, e.g., without being directly prompted by user input directing the indexing tasks. In one embodiment, by way of contrast, the generation and maintenance of indices for a conventional relational database is typically a manual task that requires user input to customize the indices.

In one embodiment, the per-column indices are used to perform queries of the graph database. In one embodiment, a client **180** may supply a query **181** and receive query results **182** from the graph database service **100**. In one embodiment, to perform a query, a query planner **130** may refer to the indices corresponding to columns associated with the query. In one embodiment, a statistics generation component **120** generates and maintains statistics for the indices in order to optimize queries. In one embodiment, the statistics generation component **120** generates and maintains sets of statistics corresponding to individual indices, such as statistics **121**A-**121**N corresponding to the indices **160**A-**160**N. In one embodiment, the statistics may be stored using any suitable storage technologies, e.g., in storage managed by or otherwise accessible to the graph database service **100**. In one embodiment, the statistics for an index may represent distributions of values within the corresponding column. In one embodiment, for example, the statistics may indicate how many times a particular value occurs within the column, how many triples having numeric values within a particular numeric range occur within the column, how many triples having string-typed values beginning with a particular character occur within the column, and so on.

In one embodiment, to optimize a query, the order of indices to be used may be determined based (at least in part) on the statistics for the per-column indices. In one embodiment, the query planner **130** uses the most constraining index first, then the next most constraining index, and so on. In one embodiment, the statistics may be maintained in real time or near-real time to enable optimized query processing using up-to-date information. In one embodiment, the generation and maintenance of statistics for an index is performed by the graph database service **100** automatically, e.g., without being directly prompted by user input directing the statistics tasks. In one embodiment, the client **180** may supply updates **183** to triples in the graph database. In one embodiment, an index and the statistics for the index are generated or updated by the graph database service **100** in response to the updating of one or more triples for the corresponding column in the graph database (e.g., the addition of one or more triples, the deletion of one or more triples, or the modification of one or more triples). In one embodiment, the graph database service **100** provides a query hint mechanism to optimize the performance of individual queries within specific applications.

In one embodiment, queries of the graph database include semantic queries. In one embodiment, a semantic query may permit the retrieval of both explicitly and implicitly derived information from the graph database based on syntactic, semantic, and structural information embodied in the database. In one embodiment, a semantic query may return a specific or precise result such as a single piece of information. In one embodiment, a semantic query may return an answer to a "fuzzier" or less specific question through pattern matching and machine logic. In one embodiment, by operating on the triples in the graph database, a semantic query may process the actual relationships between information and determine an answer from the network of connections in the graph database. In one embodiment, a semantic query may operate on structured data and utilize features such as operators (e.g., >, <, and =), pattern matching, and so on. In one embodiment, semantic queries of the graph database are formatted in the syntax of a semantic query language such as SPARQL. In one embodiment, a semantic query may be written without knowledge of a database schema in the graph database. In one embodiment, a query of the graph database may be expressed in a graph traversal language or graph query language such as Neo4j or Gremlin.

In one embodiment, the graph database is designed to effectively capture and analyze rich, dynamic data structures having complex relationships. In one embodiment, for example, a simple social query such as "find all the friends of User1's friends" may be expressed as a one-line traversal in a graph database in a graph traversal language such as Gremlin: g.V( ).has('name','User1').out('friend').out('friend').values('name'). However, using an SQL query to retrieve the same information from a relational database may be much more complex, such as the following query:

```
SELECT p1.Person AS PERSON, p2.Person AS
  FRIEND_OF_FRIEND
FROM PersonFriend pf1 JOIN Person p1
ON pf1.PersonID=p1.ID JOIN PersonFriend pf2
ON pf2.PersonID=pf1.FriendID JOIN Person p2
ON pf2.FriendID=p2.ID
WHERE p1.Person='User1' AND pf2.FriendID< >p1.ID
```

In one embodiment, the graph database service **100** may support a simple text search on property values. In one embodiment, in the property graph model, the text search may search over node and edge properties. In one embodiment, in the resource description framework (RDF) model, the text search may search over literal values. In one embodiment, the graph database service **100** may employ logic to efficiently compress and store the data so that the storage costs are lowered.

In one embodiment, the graph database service **100** may be used by clients in varying domains such as social networks, recommendation engines, data management, network and IT management, fraud detection, medical applications, Online Transaction Processing (OLTP) and Online

Analytics Processing (OLAP) workloads, and so on. In one embodiment, the graph database service **100** may be used for processing of streaming data that is rich (e.g., representing a large amount of information) and highly connected (e.g., representing many relationships). In one embodiment, for example, clients in the financial sector may use the graph database service **100** to process a stream of credit card transactions as graph queries to identify potential anomalies. In one embodiment, as a more specific example, a client of the graph database service **100** may supply a graph query to detect a purchase that takes place in one geographical region and is followed by one in another geographical region five minutes later. In one embodiment, detecting that a customer had two transactions that occurred closely together, but took place thousands of miles apart, the client of the graph database service **100** may generate an alert and send it to the customer. In one embodiment, as another example, the graph database service **100** may be used by a retail company to make purchase recommendations for a customer based on purchasing behavior of the customer's friends. In one embodiment, as yet another example, the graph database service **100** may be used by a life sciences organization to analyze the relationships between different chemicals and compounds to detect drug interactions.

In one embodiment, the graph database service **100** may be used by clients for combining and analyzing the large quantities of relationship information aggregated in the clients' OLTP and OLAP applications. In one embodiment, beyond short interactive queries (e.g., for OLTP) and longer-running complex queries (e.g., for OLAP), graph analytics using the graph database service **100** may produce new insights by analyzing entire collections of relationships. In one embodiment, graph analytics may use iterative algorithms to process very large graphs and mine them for new information. In one embodiment, examples of such graph analytics may include using search engine algorithms for detecting web page relevance, using a community detection algorithm to detect groups of similar users from a large social network, and executing a shortest path algorithm to find the lowest cost route from point A to point B on a network of roads. Such tasks may be computationally challenging for conventional databases (e.g., relational databases) because they often require visiting all of the relationships (edges) in the graph multiple times to converge on a result.

In one embodiment, the graph database service **100** supports incoming and outgoing streams of graph data. In one embodiment, the graph database service **100** may be used in conjunction with machine-learning and deep-learning applications and services such that relationship-rich data in the graph database can be analyzed to identify areas in which to use machine-learning algorithms. In one embodiment, the graph database service **100** may be used to represent and scale knowledge graphs. In one embodiment, the graph database service **100** provides native support for processing large quantities of relationship information. In one embodiment, the graph database service **100** natively supports both the property graph and resource description framework (RDF) graph models to permit flexibility in modelling data on behalf of clients. In one embodiment, queries may explore small parts of the graph (e.g. OLTP applications such as recommendation systems), explore large parts of the graph (e.g., lightweight OLAP applications such as fraud detection), or examine the whole graph repeatedly (e.g., graph analytics such as determining relevance via page rank).

In one embodiment, the graph database service **100** provides support for multiple availability zones within a provider network; if the primary cluster node fails, the graph database service **100** may automatically detect the failure, select one from the available standby cluster nodes, and promote the standby to become the new primary. In one embodiment, the graph database service **100** may propagate the DNS changes of the promoted replica so that the client's application can keep writing to the primary endpoint. In one embodiment, the graph database service **100** may also provision a new node to replace the promoted standby node in the same availability zone of the failed primary one. In case the primary node failed due to temporary availability zone disruption, the new replica may be launched automatically by the graph database service **100** once that availability zone has recovered. In one embodiment, the graph database service **100** supports snapshots (automatic and on-demand) that can be restored via the console and application programming interface (API).

In one embodiment, the client **180** may encompass any type of client suitable to submit data and requests to the graph database service **100**. In one embodiment, the client may be one of many clients of the graph database service **100**. In one embodiment, the client may include one or more services or applications that seek to make use of the graph database service **100**. In one embodiment, the client may convey network-based service requests to the service via one or more networks. In various embodiments, the network(s) may encompass any suitable combination of networking hardware and protocols necessary to establish network-based communications between the client and the graph database service **100**. In one embodiment, for example, the network(s) may generally encompass the various telecommunications networks and service providers that collectively implement the Internet. In one embodiment, the network(s) may also include private networks such as local area networks (LANs) or wide area networks (WANs) as well as public or private wireless networks. In one embodiment, for example, both the client and the graph database service **100** may be respectively provisioned within enterprises having their own internal networks. In one embodiment, the network(s) may include the hardware (e.g., modems, routers, switches, load balancers, proxy servers, etc.) and software (e.g., protocol stacks, accounting software, firewall/security software, etc.) necessary to establish a networking link between the given client and the Internet as well as between the Internet and the graph database service **100**. In one embodiment, the client may communicate with the graph database service **100** using a private network rather than the public Internet.

In one embodiment, the graph database service **100** may include one or more computing devices, any of which may be implemented by the example computing device **3000** illustrated in FIG. **14**, and any suitable storage resources. Similarly, in one embodiment, the client may be implemented using the example computing device **3000** illustrated in FIG. **14**. In various embodiments, portions of the described functionality of the service **100**, database **140**, and/or client **180** may be provided by the same computing device or by any suitable number of different computing devices. In one embodiment, if any of the components are implemented using different computing devices, then the components and their respective computing devices may be communicatively coupled, e.g., via a network. In one embodiment, each of the illustrated components (such as the graph database service **100** and its constituent components) may represent any combination of software and hardware usable to perform their respective functions. In various embodiments, the graph database service **100** and/or graph database may include additional components not shown, fewer components than shown, or different combinations, configurations, or quantities of the components shown.

FIG. **2**A illustrates an example of a graph database usable with the example system environment, including the creation of per-column indices for globally scoped column names, according to one embodiment. In one embodiment, the graph database service **100** stores data as triples in a triple table **150**. In one embodiment, the triples used in the graph database service **100** may differ from the triples in the RDF graph model, in which a triple may include a subject, predicate, and an object. In one embodiment, the storage model used by the graph database service **100** can effectively store and process both the property graph model and the RDF model using its internal triples structure. In one embodiment, in the illustrated example, the triple table includes at least the illustrated eleven triples. In one embodiment, the triples include subject identifiers **201**, column names or properties **202**, and values **203** associated with the column names or properties. In one embodiment, the subject identifiers may be referred to as identifiers or row identifiers. In one embodiment, the identifiers **201** may indicate the particular row (e.g., in a relational view of the data) or record that holds the combination of the column name and the value in the triple. In one embodiment, as shown in the example of FIG. **2**A, the same subject identifier may be reused for multiple triples, e.g., if the corresponding row or record includes values in multiple categories. In one embodiment, the column names or properties **202** may indicate a distinct and separate category of data, and the values **203** may represent one of the allowable values within the category. In one embodiment, the triples in the triple table may be used to represent nodes and edges (relationships) in a graph of connected items. In one embodiment, for example, the rows including identifier P101 may represent a node for a particular person having properties such as the name "Firstname Lastname" and the age 32. In one embodiment, the node for identifier P101 may also be connected to a node for a personal address (myAddr) A201. In one embodiment, as shown in the example, the address A201 has additional triples in the triple table indicating values for street address, city, and zip code properties. Similarly, in one embodiment, the rows including identifier B101 may represent a node for a particular business having properties such as the name "AtoZ Corporation" and a connection to a node for a business address (busAddr) A202.

In one embodiment, columns are strongly typed such that values in a particular column may share the same data type, and an enforcement mechanism may ensure that values in the particular column are limited to being expressed in the data type associated with the column. In one embodiment, data types may differ from column to column. In one embodiment, as shown in the example of FIG. **2**A, the "name" column may be associated with a string data type, while the "zip" column may be associated with a numeric data type. In one embodiment, clients are permitted to create columns that appear to be locally scoped but are actually implemented in the graph database with a global scope, e.g., by automatically appending an additional term to a potentially non-unique column name to ensure that the combination is unique in the graph database.

In one embodiment, the index creation component may create and maintain indices for every global column in the triple table. In one embodiment, the index creation component may create and maintain indices for many but not necessarily all global columns in the triple table, e.g., for columns that are intended to be queryable or searchable. In one embodiment, as shown in the example of FIG. **2**A, the index creation component may create and maintain a "name" index **160**A corresponding to the column name or property "name," a "city" index **160**B corresponding to the column name or property "city," a "zip" index **160**C corresponding to the column name or property "zip," an "age" index **160**D corresponding to the column name or property "age," a "myAddr" index **160**E corresponding to the column name or property "myAddr," a "busAddr" index **160**F corresponding to the column name or property "busAddr," and a "street" index **160**G corresponding to the column name or property "street." In one embodiment, the per-column or property-scoped indices **160**A-**160**G may be tables or other columnar data structures that include one or more rows, and each row may include the values associated with the column corresponding to the index. In one embodiment, each row in a per-column index also includes a pointer to the corresponding row in the primary table in the graph database; the pointer may take the form of a subject identifier. In one embodiment, the indices may effectively be partitioned by column name. In one embodiment, by way of contrast, such per-column indexing in a conventional relational database would often be prohibitively expensive due to the vastly greater number of locally scoped columns that may be managed in a relational database management system. In one embodiment, the generation and maintenance of indices is performed by the graph database service **100** automatically, e.g., without being directly prompted by user input directing the indexing tasks. In one embodiment, by way of contrast, the generation and maintenance of indices for a conventional relational database is typically a manual task that requires user input to customize the indices.

In various embodiments, the data elements in the graph database may include elements in addition to the subject identifiers, column names (also known as properties or predicates), and values (also known as objects or relationships). In one embodiment, the data elements may be referred to as quads, e.g., when each row potentially stores four different units of data. As illustrated in FIG. **2**B, in one embodiment, the data elements also include graph identifiers **204** that indicate particular graphs or sub-graphs to which the triples belong. As illustrated in FIG. **2**C, in one embodiment, the data elements also include one or more types of annotations **205**A-**205**G. In one embodiment, the triple table **150** stores annotations that characterize aspects of the triples, such as the values in the triples. As shown in the example of FIG. **2**C, in one embodiment, a series of annotation fields such as annotation **205**A through **205**G may be stored in the triple table. However, any suitable number and configuration of annotation fields may be used in the graph database in various embodiments. In various embodiments, the annotations may represent user-defined or user-supplied values for aspects of data such as data quality values, access rights, expiration times, and so on. In one embodiment, for a given annotation field, not all of the triples or rows may include a value for that annotation field. In the example shown in FIG. **2**C, in one embodiment, only the "P101"-"name"-"Firstname Lastname" and "B101"-"name"-"AtoZ Corporation" triples include values for the annotation field **205**A. Also in the example shown in FIG. **2**C, in one embodiment, a greater number of the triples happen to have values for the annotation field **205**G.

FIG. **3** illustrates an example of a graph database usable with the example system environment, including a relational view of data elements in the graph database, according to one embodiment. In one embodiment, the graph database is sufficiently flexible to describe rich interrelated object and relationship centric data while also achieving query performance using property-scoped, strongly typed indices. In one embodiment, as shown in the example of FIG. **3**, the graph database may reflect or represent a relational view **210** of data along with its associated per-column, property-scoped indices. In one embodiment, for example, the rows including identifier P101 may represent a row in the relational view for a particular person **220** having properties such as the name "Firstname Lastname," the age 32, and the personal address (myAddr) A201. Similarly, in one embodiment, the rows including identifier B101 may represent a row in the relational view for a particular business **230** having properties such as the name "AtoZ Corporation" and a business address (busAddr) A202. In one embodiment, the relational view may also include a table for the addresses **240** referenced in the person **220** and business **230** rows.

FIG. **4** illustrates an example of a graph database usable with the example system environment, including an entity view of data elements in the graph database, according to one embodiment. In one embodiment, the graph database may reflect or represent an entity view **250** of data along with its associated per-column, property-scoped indices. In one embodiment, the entity view may include one or more entities expressed according to JavaScript Object Notation (JSON). In one embodiment, for example, the rows including identifier P101 may represent an entity **260** in the entity (JSON) view for a particular person having properties such as the name "Firstname Lastname," the age 32, and the personal address (myAddr) A201 with nested values for a city, street, and zip code. Similarly, in one embodiment, the rows including identifier B101 may represent another entity **270** in the entity (JSON) view for a particular business having properties such as the name "AtoZ Corporation" and a business address (busAddr) A202 with nested values for a city, street, and zip code.

FIG. **5** illustrates the generation of statistics associated with per-column indices for globally scoped column names, according to one embodiment. As previously shown in the example of FIG. **2**, in one embodiment, the index creation component may create and maintain a "name" index **160**A corresponding to the column name or property "name," a "city" index **160**B corresponding to the column name or property "city," a "zip" index **160**C corresponding to the column name or property "zip," an "age" index **160**D corresponding to the column name or property "age," a "myAddr" index **160**E corresponding to the column name or property "myAddr," a "busAddr" index **160**F corresponding to the column name or property "busAddr," and a "street" index **160**G corresponding to the column name or property "street." In one embodiment, the statistics generation component generates and maintains statistics for the indices **160**A-**160**G in order to optimize queries. In one embodiment, the statistics are incrementally generated by being updated periodically as triples are added, deleted, or modified. In one embodiment, the statistics generation component generates and maintains sets of statistics corresponding to individual indices, such as statistics **121**A-**121**G corresponding to the indices **160**A-**160**G. In one embodiment, the statistics may be stored using any suitable storage technologies, e.g., in storage managed by or otherwise accessible to the graph database service **100**. In one embodiment, the statistics for an index may represent distributions of values within the corresponding column. In one embodiment, for example, the statistics may indicate how many times a particular value occurs within the column, how many triples having numeric values within a particular numeric range occur within the column, how many triples having string-typed values beginning with a particular character occur within the column, and so on.

In one embodiment, to optimize a query, the order of indices to be used may be determined based (at least in part) on the statistics **121**A-**121**G for the per-column indices **160**A-**160**G. In one embodiment, the query planner **130** uses the most constraining index first, then the next most constraining index, and so on. In one embodiment, the statistics may be maintained in real time or near-real time to enable optimized query processing using up-to-date information. In one embodiment, the generation and maintenance of statistics for an index is performed by the graph database service **100** automatically, e.g., without being directly prompted by user input directing the statistics tasks. In one embodiment, an index and the corresponding statistics for the index are updated by the graph database service **100** in response to the updating of one or more triples for the corresponding column in the graph database (e.g., the addition of one or more triples, the deletion of one or more triples, or the modification of one or more triples).

FIG. **6** is a flowchart illustrating a method for global column indexing in a graph database, according to one embodiment. In one embodiment, as shown in **610**, elements of data may be stored or updated in a graph database. In one embodiment, the elements of data in the graph database may represent triples or rows in a columnar format. In one embodiment, for example, a triple may include an identifier, a column name, and a value. In one embodiment, triples may include different elements than (e.g., in addition to or instead of) an identifier, column name, and value. In one embodiment, the identifier may also be referred to as a subject identifier. In one embodiment, the identifier may indicate the particular row (e.g., in a relational view of the data) or record that holds the combination of the column name and the value in the triple. In one embodiment, the same subject identifier may be reused for multiple triples, e.g., if the corresponding row or record includes values in multiple categories. In one embodiment, the column name may indicate a distinct and separate category of data, and the value may represent one of the allowable values within the category. In one embodiment, the triples in a graph database may be used to represent nodes and edges (relationships) in a graph of connected items. In one embodiment, the graph database may store one graph or multiple graphs. In one embodiment, the triples are also stored with graph identifiers that indicate particular graphs to which the triples belong.

In one embodiment, columns are strongly typed such that values in a particular column may share the same data type, and an enforcement mechanism may ensure that values in the particular column are limited to being expressed in the data type associated with the column. In one embodiment, data types may differ from column to column. In one embodiment, all the rows and columns in the graph database may effectively belong to the same primary table. In one embodiment, column names are globally scoped in the graph database, such that the same column name may not be represented more than once in the graph database and may not be limited to a particular sub-table of the graph database. In one embodiment, by way of contrast, column names in a conventional relational database are typically locally scoped to one of many tables.

In one embodiment, as shown in **620**, indices may be created or updated for the globally scoped columns in the primary table in the graph database. In one embodiment, indices are created and maintained for many but not necessarily all global columns in the primary table in the graph database, e.g., for columns that are intended to be queryable or searchable. In one embodiment, a per-column index may be a table or other columnar data structure that includes multiple rows, and each row may include the values associated with the column corresponding to the index. In one embodiment, a per-column index may also be referred to as a property-scoped index. In one embodiment, each row in a per-column index also includes a pointer to the row in the primary table in the graph database. In one embodiment, the indices may be stored as separate data structures from each other and from the primary table, e.g., in storage managed by or otherwise accessible to the graph database service. In one embodiment, the indices may effectively be partitioned by column name. In one embodiment, by way of contrast, such per-column indexing in a conventional relational database would often be prohibitively expensive due to the vastly greater number of locally scoped columns that may be managed in a relational database management system. In one embodiment, the generation and maintenance of indices is performed by the graph database service automatically, e.g., without being directly prompted by user input directing the indexing tasks. In one embodiment, by way of contrast, the generation and maintenance of indices for a conventional relational database is typically a manual task that requires user input to customize the indices.

In one embodiment, as shown in **630**, statistics may be generated or updated incrementally for the indices, e.g., in order to optimize queries. In one embodiment, the statistics may be stored using any suitable storage technologies, e.g., in storage managed by or otherwise accessible to the graph database service. In one embodiment, the statistics for an index may represent distributions of values within the corresponding column. In one embodiment, for example, the statistics may indicate how many times a particular value occurs within the column, how many triples having numeric values within a particular numeric range occur within the column, how many triples having string-typed values beginning with a particular character occur within the column, and so on. In one embodiment, the statistics may be maintained in real time or near-real time to enable optimized query processing using up-to-date information. In one embodiment, the generation and maintenance of statistics for an index is performed by the graph database service automatically, e.g., without being directly prompted by user input directing the statistics tasks. In one embodiment, an index and the statistics for the index are updated by the graph database service in response to the updating of one or more triples for the corresponding column in the graph database (e.g., the addition of one or more triples, the deletion of one or more triples, or the modification of one or more triples).

In one embodiment, as shown in **640**, it may be determined whether a query has been received, e.g., from a client or any user who has suitable access privileges to submit a query to the graph database service. If not, then in one embodiment, the method may await update requests to the graph database and eventually return to **610** to perform the updates (e.g., the addition of one or more triples, the deletion of one or more triples, or the modification of one or more triples). In one embodiment, if a query has been received, then as shown in **650**, the query may be performed on the graph database. In one embodiment, the query is performed (e.g., by a query planner) using the indices corresponding to column names associated with the query. In one embodiment, to optimize a query, the order of indices to be used may be determined based (at least in part) on the statistics for the per-column indices. In one embodiment, the query planner uses the most constraining index first, then the next most constraining index, and so on. In one embodiment, the query may return one or more data elements from the graph database, potentially including one or more of the values.

FIG. **7** illustrates an example system environment for query language interoperability in a graph database, according to one embodiment. In one embodiment, aspects of the graph database service **700** illustrated in FIG. **7** may be implemented as discussed above with respect to FIG. **1**. In one embodiment, for example, the graph database service **700** may include the index creation component **110**, the statistics generation component **120**, and the graph database **140** that maintains a triple table **150** and property-scoped indices **160**A-**160**N. In one embodiment, the graph database service **700** stores elements of data in the graph database using an internal data model. In one embodiment, the graph database service **700** provides access to such data elements using a plurality of different query languages. In one embodiment, the query languages are associated with various data models, and the data models associated with the query languages may differ from the internal data model in at least some respects.

In one embodiment, the internal data model of the graph database may represent elements of data as triples or rows in a columnar format. In one embodiment, triples such as triples **151**A through **151**Z may be expressed according to the internal data model and stored in the triple table; the triple table may represent a primary table in the graph database. Although triples **151**A-**151**Z are illustrated for purposes of example, any suitable number and configuration of triples may be used in the graph database in various embodiments. In one embodiment, for example, a triple according to the internal data model may include an identifier, a column name, and a value. In one embodiment, triples in the internal data model may include different elements than (e.g., in addition to or instead of) an identifier, column, name, and value, such as annotations. In one embodiment, the identifier may also be referred to as a subject identifier. In one embodiment, the identifier may indicate the particular row (e.g., in a relational view of the data) or record that holds the combination of the column name and the value in the triple. In one embodiment, the same subject identifier may be reused for multiple triples, e.g., if the corresponding row or record includes values in multiple categories. In one embodiment, the column name may indicate a distinct and separate category of data, and the value may represent one of the allowable values within the category. In one embodiment, the triples of the internal data model may be used to represent nodes and edges (relationships) in a graph of connected items. In one embodiment, the graph database may store one graph or multiple graphs. In one embodiment, the triples of the internal data model are also stored with graph identifiers that indicate particular graphs or sub-graphs to which the triples belong.

In one embodiment, columns in the internal data model are strongly typed such that values in a particular column may share the same data type, and an enforcement mechanism may ensure that values in the particular column are limited to being expressed in the data type associated with the column. In one embodiment, data types may differ from column to column internal data model. In one embodiment, all the rows and columns in the graph database may effectively belong to the same primary table, e.g., the triple table. In one embodiment, column names in the internal data model are globally scoped in the graph database, such that the same column name may not be represented more than once in the graph database and may not be limited to a particular sub-table of the graph database. In one embodiment, by way of contrast, column names in a conventional relational database are typically locally scoped to one of many tables.

In various embodiments, the graph database service **700** may provide read (or retrieve) and write (or insert) access to the triples **151**A-**151**Z using a variety of supported query languages. In one embodiment, the query languages may include graph database query languages that are typically associated with querying graph databases. In various embodiments, for example, the graph database service **700** may support graph database query languages such as SPARQL, Gremlin, and/or GraphQL. In one embodiment, the query languages supported by the graph database service **700** may include query languages typically associated with relational databases, such as Structured Query Language (SQL). In one embodiment, any of the supported query languages may be associated with a corresponding data model, and those data models may be mapped to and from the internal data model of the graph database. In one embodiment, the data models for the supported query languages may differ in at least some respects from the internal data model of the triple table **150**. In one embodiment, the graph database service **700** may support queries expressed in a graph database query language typically used for semantic queries (e.g., SPARQL) and whose data model represents the data elements as resource description framework (RDF) triples comprising subjects, predicates, and objects. In one embodiment, the graph database service **700** may support queries expressed in a graph database query language typically used for graph traversal queries (e.g., Gremlin) and whose data model represents the data elements as property graphs.

In one embodiment, the graph database service **700** may provide interoperability for the supported query languages and the corresponding data models. For example, in one embodiment, a query expressed in a first query language may insert data elements into the graph database, where the inserted data elements are mapped from a first data model to the internal data model; the same data elements may be retrieved using a query expressed in a second query language, where the retrieved data elements are mapped from the internal data model to a second data model. Similarly, in one embodiment, a query expressed in the second query language may insert data elements into the graph database, where the inserted data elements are mapped from the second data model to the internal data model; the same data elements may be retrieved using a query expressed in the first query language, where the retrieved data elements are mapped from the internal data model to the first data model. In one embodiment, the graph database service **700** may provide users with a variety of features associated with different query languages while maintaining the underlying data **151**A-**151**Z using a unified, common storage scheme according to an internal data model.

In one embodiment, one or more clients **780** may supply queries and receive query results from the graph database service. In one embodiment, as shown in FIG. **7**, the client(s) **780** may supply a query **781** expressed in a first query language and also supply another query **783** expressed in a second query language. In one embodiment, the first and second query languages may be associated with different data models, and so the form of the two queries may differ. In one embodiment, the two queries **781** and **783** may be provided by the client(s) in any order relative to each other, or potentially in a concurrent manner. In various embodiments, the queries **781** and **783** may represent insertion and/or retrieval of data elements. In one embodiment, after the first query **781** is processed by the graph database service **700**, corresponding query results **782** may be generated (based at least in part on the triple table **150**) and returned to the appropriate one of the clients **780**. In one embodiment, after the second query **783** is processed by the graph database service **700**, corresponding query results **784** may be generated (based at least in part on the triple table **150**) and returned to the appropriate one of the clients **780**. In one embodiment, the query results **782** and **784** may be expressed according to the query language of the corresponding query and may thus vary in form. In one embodiment, for example, if query **781** is expressed according to the SPARQL language, then the results **782** may be returned in a SPARQL format; similarly, if query **783** is expressed according to the Gremlin language, then the results **784** may be returned in a Gremlin format. In one embodiment, the first query **781** in one query language may insert one or more data elements into the graph database, and the second query **783** in another query language (with a different data model) may retrieve the same elements (or a portion thereof) from the graph database.

In one embodiment, the graph database service **700** includes a query interface **710** that supports multiple query languages. In one embodiment, the query interface **710** represents a unified interface for receiving queries and returning query results according to a plurality of query languages that differ in their data models. In one embodiment, the query interface **710** may include any suitable elements of graphical user interfaces (GUIs), command-line interfaces (CLIs), application programming interfaces (APIs), other suitable types of user interfaces, and/or other suitable types of programmatic interfaces. In one embodiment, the query interface **710** receives queries in a variety of query languages and automatically detects the query language by identifying any keywords and/or syntax associated with the query language. In various embodiments, the query interface **710** (or another suitable component of the graph database service **700**) may perform operations such as query parsing, syntactic validation, and/or semantic validation. In one embodiment, the query parsing, syntactic validation, and/or semantic validation may be specific to the query language in which the query is expressed.

In one embodiment, the graph database service **700** uses a partitioned indexing scheme to enable querying of the graph database using any of the supported query languages. In one embodiment, the index creation component **110** may create and maintain indices for every global column in the primary table in the graph database. In one embodiment, the index creation component **110** may create and maintain indices for many but not necessarily all global columns in the primary table in the graph database, e.g., for columns that are intended to be queryable or searchable. In one embodiment, a per-column index may be a table or other columnar data structure that includes multiple rows, and each row may include the values associated with the column corresponding to the index. In one embodiment, a per-column index may also be referred to as a property-scoped index. In one embodiment, each row in a per-column index also includes a pointer to the corresponding row in the primary table in the graph database. In one embodiment, the indices **160**A-**160**N may be stored as separate data structures from each other and from the triple table **150**, e.g., in storage managed by or otherwise accessible to the graph database service. In one embodiment, the indices may effectively be partitioned by column name. In one embodiment, by way of contrast, such per-column indexing in a conventional relational database would often be prohibitively expensive due to the vastly greater number of locally scoped columns that may be managed in a relational database management system. In one embodiment, the generation and maintenance of indices is performed by the graph database service **700** automatically, e.g., without being directly prompted by user input directing the indexing tasks. In one embodiment, by way of contrast, the generation and maintenance of indices for a conventional relational database is typically a manual task that requires user input to customize the indices.

In one embodiment, the graph database service **700** includes a query planner **730** that optimizes queries and generates execution plans. In one embodiment, to perform a query, the query planner **730** may refer to the indices corresponding to columns associated with the query. In one embodiment, a statistics generation component **120** generates and maintains statistics for the indices in order to optimize queries. In one embodiment, the statistics generation component **120** generates and maintains sets of statistics corresponding to individual indices, such as statistics **121**A-**121**N corresponding to the indices **160**A-**160**N. In one embodiment, the statistics may be stored using any suitable storage technologies, e.g., in storage managed by or otherwise accessible to the graph database service **700**. In one embodiment, the statistics for an index may represent distributions of values within the corresponding column. In one embodiment, for example, the statistics may indicate how many times a particular value occurs within the column, how many triples having numeric values within a particular numeric range occur within the column, how many triples having string-typed values beginning with a particular character occur within the column, and so on.

In one embodiment, to optimize a query using the query planner **730**, the order of indices to be used may be determined based (at least in part) on the statistics for the per-column indices. In one embodiment, the query planner **730** uses the most constraining index first, then the next most constraining index, and so on. In one embodiment, the statistics may be maintained in real time or near-real time to enable optimized query processing using up-to-date information. In one embodiment, the generation and maintenance of statistics for an index are performed by the graph database service **700** automatically, e.g., without being directly prompted by user input directing the statistics tasks. In one embodiment, an index and the statistics for the index are generated or updated by the graph database service **700** in response to the updating of one or more triples for the corresponding column in the graph database (e.g., the addition of one or more triples, the deletion of one or more triples, or the modification of one or more triples). In one embodiment, the graph database service **700** provides a query hint mechanism to optimize the performance of individual queries within specific applications.

In one embodiment, the query planner **730** may generate a query plan. In one embodiment, the query plan may include any suitable data and/or instructions to implement the query, such as an execution path tree. In one embodiment, the execution plans for queries differing in their query language may take a similar form that is essentially independent of the originating query language and/or its data model. In one embodiment, the graph database service **700** includes a query execution component **740**, also referred to as an execution engine. In one embodiment, the execution engine may execute or otherwise implement execution plans that were generated for queries differing in their query language. In one embodiment, the execution engine may represent a unified, common platform for executing queries for multiple query languages that differ in their data model. In one embodiment, the execution engine may interact with the property-scoped indices **160**A-**160**N to perform operations such as insertion of data elements into the triple table **150** and retrieval of data elements from the triple table.

FIG. **8**A illustrates further aspects of the example system environment for query language interoperability in a graph database, including separate components for multiple query languages in a query pipeline, according to one embodiment. In one embodiment, the functionality of the query interface **710** as discussed above may be distributed among a plurality of language-specific query interface components. In one embodiment, for example, the graph database service **700** includes query interfaces **710**A through **710**E, each of which may receive queries expressed in one or more corresponding query languages. In one embodiment, one of the client(s) **780** may choose which of the query interfaces **710**A-**710**E to use based on the query language in which the client seeks to express the query. In various embodiments, any suitable number and configuration of query interfaces **710**A-**710**E may be used in the graph database system **700**. In one embodiment, the query interfaces **710**A-**710**E may perform operations such as query parsing, syntactic validation, and/or semantic validation in a manner specific to the query language(s) associated with the component.

In one embodiment, the functionality of the query planner **730** as discussed above may be distributed among a plurality of language-specific query planner components. In one embodiment, for example, the graph database service **700** includes query interfaces **730**A through **730**E, each of which may optimize queries and generate query plans for queries expressed in one or more corresponding query languages. In one embodiment, any of the query interfaces **730**A-**730**E may be part of a query pipeline that also includes one of the language-specific query interface components **710**A-**710**E. In one embodiment, the query planner **730**A-**730**E used for a particular query may vary based on the query interface component **710**A-**710**E. In various embodiments, any suitable number and configuration of query interfaces **730**A-**730**E may be used in the graph database system **700**. In one embodiment, the execution plans generated by the various query planning components **730**A-**730**E may take a similar form that is essentially independent of the originating query language and/or data model. In one embodiment, query plans generated using the query planning components **730**A-**730**E may be executed by the same execution engine **740** as discussed above with respect to FIG. **7**. In one embodiment, as illustrated in FIG. **8**B, a plurality of language-specific query planners **730**A-**730**E may be used in a pipeline with a unified query interface **710** for multiple query languages. In one embodiment, as illustrated in FIG. **8**C, a plurality of language-specific query interfaces **710**A-**710**E may be used in a pipeline with a unified query planner **730** for multiple query languages.

In one embodiment, queries of the graph database may include semantic queries expressed according to any of the supported query languages. In one embodiment, a semantic query may permit the retrieval of both explicitly and implicitly derived information from the graph database based on syntactic, semantic, and structural information embodied in the database. In one embodiment, a semantic query may return a specific or precise result such as a single piece of information. In one embodiment, a semantic query may return an answer to a "fuzzier" or less specific question through pattern matching and machine logic. In one embodiment, by operating on the triples in the graph database, a semantic query may process the actual relationships between information and determine an answer from the network of connections in the graph database. In one embodiment, a semantic query may operate on structured data and utilize features such as operators (e.g., >, <, and =), pattern matching, and so on. In one embodiment, semantic queries of the graph database are formatted in the syntax of a query language such as SPARQL that is particularly suited for semantic queries and may be referred to as a semantic query language. In one embodiment, a semantic query may be written without knowledge of a database schema in the graph database. In one embodiment, a query of the graph database may be expressed in a query language such as Gremlin that is particularly suited for graph traversal queries and may be referred to as a graph traversal language or graph query language. In one embodiment, the form of a semantic query may differ from the form of a graph traversal query. In one embodiment, both semantic queries and graph traversal queries may be mapped to and from the internal data model of the graph database. In one embodiment, the graph database service **700** may support queries that perform a simple text search on property values. In one embodiment, in the property graph model associated with one or more query languages such as Gremlin, the text search may search over node and edge properties. In one embodiment, in the resource description framework (RDF) model associated with one or more query languages such as SPARQL, the text search may search over literal values.

In one embodiment, the graph database service **700** may be used by client(s) **780** in varying domains such as social networks, recommendation engines, data management, network and IT management, fraud detection, medical applications, Online Transaction Processing (OLTP) and Online Analytics Processing (OLAP) workloads, and so on. In one embodiment, the graph database service **700** may be used for processing of streaming data that is rich (e.g., representing a large amount of information) and highly connected (e.g., representing many relationships). In one embodiment, for example, clients in the financial sector may use the graph database service **700** to process a stream of credit card transactions as graph queries to identify potential anomalies. In one embodiment, as a more specific example, a client of the graph database service **700** may supply a graph query to detect a purchase that takes place in one geographical region and is followed by one in another geographical region five minutes later. In one embodiment, detecting that a customer had two transactions that occurred closely together, but took place thousands of miles apart, the client of the graph database service **700** may generate an alert and send it to the customer. In one embodiment, as another example, the graph database service **700** may be used by a retail company to make purchase recommendations for a customer based on purchasing behavior of the customer's friends. In one embodiment, as yet another example, the graph database service **700** may be used by a life sciences organization to analyze the relationships between different chemicals and compounds to detect drug interactions. In various embodiments, these use cases may be implemented using one or more supported query languages that are mapped to and from the internal data model of the graph database **140**.

In one embodiment, the graph database service may be used by client(s) **780** for combining and analyzing the large quantities of relationship information aggregated in the clients' OLTP and OLAP applications. In one embodiment, beyond short interactive queries (e.g., for OLTP) and longer-running complex queries (e.g., for OLAP), graph analytics using the graph database service may produce new insights by analyzing entire collections of relationships. In one embodiment, graph analytics may use iterative algorithms to process very large graphs and mine them for new information. In one embodiment, examples of such graph analytics may include using search engine algorithms for detecting web page relevance, using a community detection algorithm to detect groups of similar users from a large social network, and executing a shortest path algorithm to find the lowest cost route from point A to point B on a network of roads. Such tasks may be computationally challenging for conventional databases (e.g., relational databases) because they often require visiting all of the relationships (edges) in the graph multiple times to converge on a result. In various embodiments, these graph analytics cases may be implemented using one or more supported query languages that are mapped to and from the internal data model of the graph database **140**.

In one embodiment, the graph database service **700** supports incoming and outgoing streams of graph data. In one embodiment, the graph database service **700** may be used in conjunction with machine-learning and deep-learning applications and services such that relationship-rich data in the graph database can be analyzed to identify areas in which to use machine-learning algorithms. In one embodiment, the graph database service **700** may be used to represent and scale knowledge graphs. In one embodiment, the graph database service **700** provides native support for processing large quantities of relationship information. In one embodiment, by supporting a variety of query languages, the graph database service **700** supports both the property graph and resource description framework (RDF) graph models to permit flexibility in querying data on behalf of clients.

In one embodiment, the client(s) **780** may encompass any type of client suitable to submit data and requests to the graph database service **700**. In one embodiment, the client(s) **780** may include one or more services or applications that seek to make use of the graph database service **700**. In one embodiment, the client(s) **780** may convey network-based service requests to the service via one or more networks. In various embodiments, the network(s) may encompass any suitable combination of networking hardware and protocols necessary to establish network-based communications between the client and the graph database service. In one embodiment, for example, the network(s) may generally encompass the various telecommunications networks and service providers that collectively implement the Internet. In one embodiment, the network(s) may also include private networks such as local area networks (LANs) or wide area networks (WANs) as well as public or private wireless networks. In one embodiment, for example, both the client(s) **780** and the graph database service **700** may be respectively provisioned within enterprises having their own internal networks. In one embodiment, the network(s) may include the hardware (e.g., modems, routers, switches, load balancers, proxy servers, etc.) and software (e.g., protocol stacks, accounting software, firewall/security software, etc.) necessary to establish a networking link between the given client and the Internet as well as between the Internet and the graph database service. In one embodiment, the client(s) **780** may communicate with the graph database service using a private network rather than the public Internet.

In one embodiment, the graph database service **700** may include one or more computing devices, any of which may be implemented by the example computing device **3000** illustrated in FIG. **14**, and any suitable storage resources. Similarly, in one embodiment, the client(s) **780** may be implemented using the example computing device **3000** illustrated in FIG. **14**. In various embodiments, portions of the described functionality of the service **700**, database **140**, and/or client(s) **780** may be provided by the same computing device or by any suitable number of different computing devices. In one embodiment, if any of the components are implemented using different computing devices, then the components and their respective computing devices may be communicatively coupled, e.g., via a network. In one embodiment, each of the illustrated components (such as the graph database service and its constituent components) may represent any combination of software and hardware usable to perform their respective functions. In various embodiments, the graph database service and/or graph database may include additional components not shown, fewer components than shown, or different combinations, configurations, or quantities of the components shown.

FIG. **9** illustrates an example of a graph database that supports query language interoperability, including insertion of data elements expressed according to a resource description framework (RDF) data model, according to one embodiment. In one embodiment, the graph database service **700** may support queries expressed in a graph database query language typically used for semantic queries (e.g., SPARQL) and whose data model represents the data elements as resource description framework (RDF) triples comprising subjects, predicates, and objects. In one embodiment, a semantic query may operate on structured data and utilize features such as operators (e.g., >, <, and =), pattern matching, and so on. In one embodiment, semantic queries of the graph database are formatted in the syntax of a query language such as SPARQL that is particularly suited for semantic queries and may be referred to as a semantic query language. In one embodiment, a semantic query may be written without knowledge of a database schema in the graph database. In one embodiment, the graph database service **700** may support queries in SPARQL or another semantic query language to insert one or more triples into a graph, delete one or more triples from a graph, load the contents of a document representing a graph into the graph database, and clear all the triples in one or more graphs. In one embodiment, performing such a query may include a data model mapping operation **720** in which elements of data in the "source" data model of the query are mapped to elements of data as expressed in the internal data model of the triple table **150**. In one embodiment, as shown in the example of FIG. **9**, an RDF-based query **900** (expressed in a query language such as SPARQL) may be processed to insert a triple (subject, predicate, object) as at least one subject ID, column name, and value in the triple table **150**.

In various embodiments, any suitable mapping may be used between RDF-based queries and the triple table **150**. In one embodiment, for example, subjects in an RDF-based query may be mapped to subject IDs in the triple table **150**, predicates may be mapped to column names, and objects may be mapped to values. In one embodiment, an RDF graph construct may be mapped to a container construct in the triple table **150**. In one embodiment, the RDF-based insertion query **900** may be formatted according to the following example, where the subject <P105> may be mapped to a subject ID in the triple table **150**, the predicates ("type," "name," and "age") may be mapped to column names in the triple table, and the objects of those predicates may be mapped to values in the triple table:

```
INSERT DATA
{
  <P105> type  <Customer>
  <P105> name "Name Surname"
  <P105> age    27
}
```

In one embodiment, the RDF-based insertion query **900** may include one or more additional fields such as in the following example, where the triples are associated with a graph identifier (http://customerList) that is mapped to a graph ID previously illustrated in FIG. **2**B:

```
INSERT DATA
{
  GRAPH <http://customerList>
  {
    <P105> type  <Customer>
    <P105> name "Name Surname"
    <P105> age    27
  }
}
```

FIG. **10** illustrates an example of a graph database that supports query language interoperability, including insertion of data elements expressed according to a property graph data model, according to one embodiment. In one embodiment, the graph database service **700** may support queries expressed in a graph database query language typically used for graph traversal queries (e.g., Gremlin) and whose data model represents the data elements as property graphs. In one embodiment, the form of a graph traversal query may differ from the form of a semantic query. In one embodiment, both semantic queries and graph traversal queries may be mapped to and from the internal data model of the graph database. In one embodiment, as shown in the example of FIG. **10**, a property-graph-based query **1000** (expressed in a query language such as Gremlin) may be processed to insert one or more nodes or edges (or properties thereof) of a property graph as at least one subject ID, column name, and value in the triple table **150**. In one embodiment, performing such a query may include a data model mapping operation **720** in which elements of data in the "source" data model of the query **1000** are mapped to elements of data as expressed in the internal data model of the triple table **150**.

In various embodiments, any suitable mapping may be used between property-graph-based queries and the triple table **150**. In one embodiment, to achieve a similar result as the RDF-based insertion query **900**, a property-graph-based insertion query **1000** may be formatted according to the following example:

graph.addVertex('type', 'Customer', 'id', '<P105>', 'name', 'Name Surname', 'age', '27')

In one embodiment, the property-graph-based insertion query **1000** may include one or more additional fields such as in the following example, where the inserted values are associated with a graph identifier (http://customerList) that is mapped to a graph ID previously illustrated in FIG. **2**B:

graph.addVertex('type', 'Customer', 'id', '<P105>', '_container', '<http://customerList>', 'name', 'Name Surname', 'age', '27')

FIG. **11** illustrates an example of a graph database that supports query language interoperability, including retrieval of data elements expressed according to an RDF data model, according to one embodiment. In one embodiment, the graph database service **700** may support queries that perform a simple text search on property values. In one embodiment, in the RDF model associated with one or more query languages such as SPARQL, the text search may search over literal values. In one embodiment, the graph database service **700** may support queries in SPARQL or another semantic query language to select values from the graph database and return them in a tabular format, construct information extracted from the graph database and transform it into an RDF form, ask for a true/false result of a query, and describe an extracted RDF graph extracted from the graph database. In one embodiment, performing such a query may include a data model mapping operation **720** in which elements of data in the internal data model are mapped to and from elements of data as expressed in the data model associated with the query language. In one embodiment, as shown in the example of FIG. **11**, an RDF-based query **1100** (expressed in a query language such as SPARQL) may be processed to select one or more triples (subject, predicate, object) from the triple table **150**. In one embodiment, the RDF-based query results **1105** may be retrieved from the triple table, mapped to RDF triples using the data model mapping **720**, and returned to the appropriate client.

FIG. **12** illustrates an example of a graph database that supports query language interoperability, including retrieval of data elements expressed according to a property graph data model, according to one embodiment. In one embodiment, the graph database service **700** may support queries that perform a simple text search on property values. In one embodiment, in the property graph model associated with one or more query languages such as Gremlin, the text search may search over node and edge properties. In one embodiment, performing such a query may include a data model mapping operation **720** in which elements of data in the internal data model are mapped to and from elements of data as expressed in the data model associated with the query language. In one embodiment, as shown in the example of FIG. **12**, a property-graph-based query **1200** (expressed in a query language such as Gremlin) may be processed to select one or more nodes, edges, or properties thereof from the triple table **150**. In one embodiment, the property-graph-based query results **1205** may be retrieved from the triple table, mapped to the property graph data model using the data model mapping **720**, and returned to the appropriate client.

FIG. **13** is a flowchart illustrating a method for implementing query language interoperability in a graph database, according to one embodiment. In one embodiment, as shown in **1310**, a first query may be received at a graph database service or system. In one embodiment, the first query may seek to insert one or more data elements into the graph database. In one embodiment, the first query may be expressed in one particular query language of a supported set of query languages. In one embodiment, the query languages may include at least two graph database query languages that are typically associated with querying graph databases. In various embodiments, for example, the graph database may be accessed with graph database query languages such as SPARQL, Gremlin, and/or GraphQL. In one embodiment, any of the supported query languages may be associated with a corresponding data model. In one embodiment, the first query may be expressed in a graph database query language typically used for semantic queries (e.g., SPARQL) and whose data model represents the data elements as resource description framework (RDF) triples comprising subjects, predicates, and objects. In one embodiment, the first query may be expressed in a graph database query language typically used for graph traversal queries (e.g., Gremlin) and whose data model represents the data elements as property graphs.

In one embodiment, as shown in **1320**, the data elements may be stored in the graph database using an internal data model. In one embodiment, the internal data model differs in at least some respects from the data model associated with the query language in which the first query was expressed. In one embodiment, for example, the internal data model represents data as triples of subject identifiers, column names, and values, while the data model associated with the first query may express data as RDF triples (with subjects, predicates, and objects) or property graphs (with nodes and edges). In one embodiment, the data elements may be mapped to the internal data model from the data model associated with the first query.

In one embodiment, columns in the internal data model are strongly typed such that values in a particular column may share the same data type, and an enforcement mechanism may ensure that values in the particular column are limited to being expressed in the data type associated with the column. In one embodiment, column names in the internal data model are globally scoped in the graph database, such that the same column name may not be represented more than once in the graph database and may not be limited to a particular sub-table of the graph database. In one embodiment, indices may be created or updated for the globally scoped columns in the internal data model in the graph database. In one embodiment, indices are created and maintained for many but not necessarily all global columns in the primary table in the graph database, e.g., for columns that are intended to be queryable or searchable. In one embodiment, a per-column index may be a table or other columnar data structure that includes multiple rows, and each row may include the values associated with the column corresponding to the index. In one embodiment, statistics may be generated or updated incrementally for the indices, e.g., in order to optimize queries. In one embodiment, the statistics for an index may represent distributions of values within the corresponding column. In one embodiment, for example, the statistics may indicate how many times a particular value occurs within the column, how many triples having numeric values within a particular numeric range occur within the column, how many triples having string-typed values beginning with a particular character occur within the column, and so on. In one embodiment, the generation and maintenance of indices and statistics is performed by the graph database service automatically, e.g., without being directly prompted by user input directing the indexing tasks.

In one embodiment, as shown in **1330**, at least some of the data elements inserted using the first query may be retrieved from the graph database based (at least in part) on a second query. In one embodiment, the second query is expressed in a query language that differs from the query language in which the first query was expressed. For example, in one embodiment, the data elements may be inserted using a query expressed in a semantic query language such as SPARQL and retrieved (at least in part) using a query expressed in a graph traversal language such as Gremlin. As another example, in one embodiment, the data elements may be inserted using a query expressed in a graph traversal language such as Gremlin and retrieved (at least in part) using a query expressed in a semantic query language such as SPARQL. In one embodiment, the data elements may be mapped from the internal data model to the data model associated with the second query. In one embodiment, the query is performed (e.g., by a query planner) using the indices corresponding to column names (as represented in the internal data model) associated with the query. In one embodiment, to optimize a query, the order of indices to be used may be determined based (at least in part) on the statistics for the per-column indices. In one embodiment, the query planner uses the most constraining index first, then the next most constraining index, and so on. In one embodiment, the graph database may provide interoperability of a plurality of supported query languages (and their associated data models) using a common storage scheme.

Illustrative Computer System

In one embodiment, a computer system that implements a portion or all of one or more of the technologies described herein may include a computer system that includes or is configured to access one or more computer-readable media. FIG. **14** illustrates such a computing device **3000** in one embodiment. In one embodiment, computing device **3000** includes one or more processors **3010**A-**3010**N coupled to a system memory **3020** via an input/output (I/O) interface **3030**. In one embodiment, computing device **3000** further includes a network interface **3040** coupled to I/O interface **3030**.

In various embodiments, computing device **3000** may be a uniprocessor system including one processor or a multiprocessor system including several processors **3010**A-**3010**N (e.g., two, four, eight, or another suitable number). In various embodiments, processors **3010**A-**3010**N may include any suitable processors capable of executing instructions. For example, in various embodiments, processors **3010**A-**3010**N may be processors implementing any of a variety of instruction set architectures (ISAs), such as the x86, PowerPC, SPARC, or MIPS ISAs, or any other suitable ISA. In one embodiment, in multiprocessor systems, each of processors **3010**A-**3010**N may commonly, but not necessarily, implement the same ISA.

In one embodiment, system memory **3020** may be configured to store program instructions and data accessible by processor(s) **3010**A-**3010**N. In various embodiments, system memory **3020** may be implemented using any suitable memory technology, such as static random access memory (SRAM), synchronous dynamic RAM (SDRAM), nonvolatile/Flash-type memory, or any other type of memory. In one embodiment, program instructions and data implementing one or more desired functions, such as those methods, techniques, and data described above, are shown stored within system memory **3020** as code (i.e., program instructions) **3025** and data **3026**.

In one embodiment, I/O interface **3030** may be configured to coordinate I/O traffic between processors **3010**A-**3010**N, system memory **3020**, and any peripheral devices in the device, including network interface **3040** or other peripheral interfaces. In some embodiments, I/O interface **3030** may perform any necessary protocol, timing or other data transformations to convert data signals from one component (e.g., system memory **3020**) into a format suitable for use by another component (e.g., processor **3010**). In some embodiments, I/O interface **3030** may include support for devices attached through various types of peripheral buses, such as a variant of the Peripheral Component Interconnect (PCI) bus standard or the Universal Serial Bus (USB) standard, for example. In some embodiments, the function of I/O interface **3030** may be split into two or more separate components, such as a north bridge and a south bridge, for example. In some embodiments, some or all of the functionality of I/O interface **3030**, such as an interface to system memory **3020**, may be incorporated directly into processors **3010**A-**3010**N.

In one embodiment, network interface **3040** may be configured to allow data to be exchanged between computing device **3000** and other devices **3060** attached to a network or networks **3050**. In various embodiments, network interface **3040** may support communication via any suitable wired or wireless general data networks, such as types of Ethernet network, for example. In one embodiment, network interface **3040** may support communication via telecommunications/telephony networks such as analog voice networks or digital fiber communications networks, via storage area networks such as Fibre Channel SANs, or via any other suitable type of network and/or protocol.

In some embodiments, system memory **3020** may be one embodiment of a computer-readable (i.e., computer-accessible) medium configured to store program instructions and data as described above for implementing embodiments of the corresponding methods and apparatus. However, in some embodiments, program instructions and/or data may be received, sent or stored upon different types of computer-readable media. In one embodiment, generally speaking, a computer-readable medium may include non-transitory storage media or memory media such as magnetic or optical media, e.g., disk or DVD/CD coupled to computing device **3000** via I/O interface **3030**. In one embodiment, a non-transitory computer-readable storage medium may also include any volatile or non-volatile media such as RAM (e.g. SDRAM, DDR SDRAM, RDRAM, SRAM, etc.), ROM, etc., that may be included in some embodiments of computing device **3000** as system memory **3020** or another type of memory. In one embodiment, a computer-readable medium may include transmission media or signals such as electrical, electromagnetic, or digital signals, conveyed via a communication medium such as a network and/or a wireless link, such as may be implemented via network interface **3040**. Portions or all of multiple computing devices such as that illustrated in FIG. **14** may be used to implement the described functionality in various embodiments; for example, software components running on a variety of different devices and servers may collaborate to provide the functionality. In some embodiments, portions of the described functionality may be implemented using storage devices, network devices, or various types of computer systems. In one embodiment, the term "computing device" refers to at least all these types of devices, and is not limited to these types of devices.

The various methods as illustrated in the Figures and described herein represent examples of embodiments of methods. In various embodiments, the methods may be implemented in software, hardware, or a combination thereof. In various ones of the methods, the order of the steps may be changed, and various elements may be added, reordered, combined, omitted, modified, etc. In various embodiments, various ones of the steps may be performed automatically (e.g., without being directly prompted by user input) and/or programmatically (e.g., according to program instructions).

The terminology used in the description of the invention herein is for the purpose of describing particular embodiments only and is not intended to be limiting of the invention. As used in the description of the invention and the appended claims, the singular forms "a", "an" and "the" are intended to include the plural forms as well, unless the context clearly indicates otherwise. It will also be understood that the term "and/or" as used herein refers to and encompasses any and all possible combinations of one or more of the associated listed items. It will be further understood that the terms "includes," "including," "comprises," and/or "comprising," when used in this specification, specify the presence of stated features, integers, steps, operations, elements, and/or components, but do not preclude the presence or addition of one or more other features, integers, steps, operations, elements, components, and/or groups thereof.

As used herein, the term "if" may be construed to mean "when" or "upon" or "in response to determining" or "in response to detecting," depending on the context. Similarly, the phrase "if it is determined" or "if [a stated condition or event] is detected" may be construed to mean "upon determining" or "in response to determining" or "upon detecting [the stated condition or event]" or "in response to detecting [the stated condition or event]," depending on the context.

It will also be understood that, although the terms first, second, etc., may be used herein to describe various elements, these elements should not be limited by these terms. These terms are only used to distinguish one element from another. For example, a first contact could be termed a second contact, and, similarly, a second contact could be termed a first contact, without departing from the scope of the present invention; the first contact and the second contact are both contacts, but they are not the same contact.

Numerous specific details are set forth herein to provide a thorough understanding of claimed subject matter. However, it will be understood by those skilled in the art that claimed subject matter may be practiced without these specific details. In other instances, methods, apparatus, or systems that would be known by one of ordinary skill have not been described in detail so as not to obscure claimed subject matter. Various modifications and changes may be made as would be obvious to a person skilled in the art having the benefit of this disclosure. It is intended to embrace all such modifications and changes and, accordingly, the above description is to be regarded in an illustrative rather than a restrictive sense.

What is claimed is:

1. A method, comprising:

inserting, according to respective query requests received via one or more query interfaces, a plurality of data elements into a database configured to store information corresponding to graphs, the respective query requests expressed using a plurality of query languages respectively associated with a plurality of data formats, wherein inserting respective data elements of the plurality of data elements comprises:

automatically indexing the data element according to an internal data format different from individual ones of the plurality of data formats; and

storing the data element in the database using the internal data format; and

retrieving at least one data element of the plurality of data elements from the database based at least in part on a query expressed using a query language different from a query language of the plurality of query languages used in inserting the at least one data element.

2. The method as recited in claim **1**, wherein the plurality of data formats comprises:

a first data model that represents data elements using resource description framework (RDF) triples comprising subjects, predicates, and objects; and

a second data model that represents data elements using property graphs.

3. The method as recited in claim **2**, wherein a set of the plurality of data elements is inserted into the database based at least in part on mapping one or more RDF triples to the internal data model, and wherein the set of the data elements are retrieved from the database based at least in part on mapping the internal data model to one or more property graphs.

4. The method as recited in claim **2**, wherein a set of the plurality of data elements are inserted into the database based at least in part on mapping one or more property graphs to the internal data model, and wherein the set of the data elements is retrieved from the database based at least in part on mapping the internal data model to one or more RDF triples.

5. The method as recited in claim **1**, further comprising:

retrieving an additional one or more of the plurality data elements from the database based at least in part on an additional query, wherein the query and the additional query are expressed using different query languages.

6. The method as recited in claim **5**, further comprising:

generating a query execution plan based at least in part on the query;

generating an additional query execution plan based at least in part on the additional query; and

executing the query execution plan and the additional query execution plan using a query execution engine.

7. The method as recited in claim **1**, wherein the internal data format represents the data elements using subject identifiers, column names, and values for the column names, wherein the column names are globally scoped in the database, and wherein the column names are associated with respective data types for the values.

8. The method as recited in claim **7**, further comprising:

creating indices corresponding to the column names, wherein an individual one of the indices comprises one or more of the values associated with the corresponding column name, and wherein the query is performed using one or more of the indices corresponding to one of more of the column names associated with the query.

9. A distributed system, comprising:

a plurality of computing devices respectively comprising one or more processors and a memory, the memory storing instructions that upon execution on or across the one or more processors cause the one or more computing devices to implement a database configured to:

insert, according to respective query requests received via one or more query interfaces, a plurality of data elements as information corresponding to graphs, the respective query requests expressed using a plurality of query languages respectively associated with a plurality of data formats, wherein to insert respective data elements of the plurality of data elements, the database is configured to:

automatically index the data element according to an internal data format different from individual ones of the plurality of data formats; and

store the data element using the internal data format; and

retrieve at least one data element of the plurality of data elements based at least in part on a query expressed using a query language different from a query language of the plurality of query languages used in inserting the at least one data element.

10. The distributed system as recited in claim **9**, where respective ones of the plurality of computing devices are located in different ones of a plurality of availability zones.

11. The distributed system as recited in claim **9**, wherein the database is further configured to:

automatically partition storage of the database according to respective column names of the plurality of data elements in the internal data format.

12. The distributed system as recited in claim **9**, wherein the plurality of data formats comprises:
   a first data model that represents data elements using resource description framework (RDF) triples comprising subjects, predicates, and objects; and
   a second data model that represents data elements using property graphs.

13. The distributed system as recited in claim **12**, wherein a set of the plurality of data elements is inserted into the database based at least in part on mapping one or more RDF triples to the internal data model, and wherein the set of the data elements are retrieved from the database based at least in part on mapping the internal data model to one or more property graphs.

14. The distributed system as recited in claim **12**, wherein a set of the plurality of data elements are inserted into the database based at least in part on mapping one or more property graphs to the internal data model, and wherein the set of the data elements is retrieved from the database based at least in part on mapping the internal data model to one or more RDF triples.

15. One or more non-transitory computer-accessible storage media storing program instructions that when executed on or across one or more processors cause one or more computer systems to perform:
   inserting, according to respective query requests received via one or more query interfaces, a plurality of data elements into a database configured to store information corresponding to graphs, the respective query requests expressed using a plurality of query languages respectively associated with a plurality of data formats, wherein inserting respective data elements of the plurality of data elements comprises:
      automatically indexing the data element according to an internal data format different from individual ones of the plurality of data formats; and
      storing the data element in the database using the internal data format; and
   retrieving at least one data element of the plurality of data elements from the database based at least in part on a query expressed using a query language different from a query language of the plurality of query languages used in inserting the at least one data element.

16. The one or more non-transitory computer-accessible storage media as recited in claim **15**, wherein the plurality of data formats comprises:
   a first data model that represents data elements using resource description framework (RDF) triples comprising subjects, predicates, and objects; and
   a second data model that represents data elements using property graphs.

17. The one or more non-transitory computer-accessible storage media as recited in claim **15**, wherein the program instructions are further computer-executable to perform:
   retrieving an additional one or more of the plurality data elements from the database based at least in part on an additional query, wherein the query and the additional query are expressed using different query languages.

18. The one or more non-transitory computer-accessible storage media as recited in claim **17**, wherein the program instructions are further computer-executable to perform:
   generating a query execution plan based at least in part on the query;
   generating an additional query execution plan based at least in part on the additional query; and
   executing the query execution plan and the additional query execution plan using a query execution engine.

19. The one or more non-transitory computer-accessible storage media as recited in claim **15**, wherein the internal data format represents the data elements using subject identifiers, column names, and values for the column names, wherein the column names are globally scoped in the database, and wherein the column names are associated with respective data types for the values.

20. The one or more non-transitory computer-accessible storage media as recited in claim **19**, wherein the program instructions are further computer-executable to perform:
   creating indices corresponding to the column names, wherein an individual one of the indices comprises one or more of the values associated with the corresponding column name, and wherein the query is performed using one or more of the indices corresponding to one of more of the column names associated with the query.

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